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PREVENTION REFERENCE MANUAL:
CHEMICAL SPECIFIC
VOLUME 15: CONTROL OF ACCIDENTAL RELEASES OF SULFUR TRIOXIDE

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16. ABSTRACT The report, discussing sulfur trioxide (SO3), is one of a series addressing the prevention of accidental releases of toxic chemicals. SO3, a clear oily liquid or solid at typical ambient conditions, has an Immediately Dangerous to Life and Health (IDLH) concentration of 20 ppm, which makes it an acutely toxic hazard. Reducing the risk associated with an accidental release of SO3 involves identifying some of the potential causes of accidental releases that apply to process facilities than manufacture or use the chemical. The manual identifies examples of potential causes and measures that may be taken to reduce the accidental release risk. Such measures include recommendations on plant design practices, prevention, protection, and mitigation technologies, and operation and maintenance practices. Conceptual cost estimates of example prevention, protection, and mitigation measures are provided.

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ABSTRACT

The accidental release of a toxic chemical at Bhopal, India, in 1984 was a milestone in creating an increased public awareness of toxic release problems. As a result of other, perhaps less dramatic incidents in the past, portions of the chemical industry were aware of this problem long before these events. These same portions of the industry have made advances in this area. Interest in reducing the probability and consequences of accidental toxic chemical releases that might harm workers within a process facility and people in the surrounding community prompted the preparation of this manual and a series of companion manuals addressing accidental releases of toxic chemicals.

Sulfur trioxide, a clear oily liquid or solid at typical ambient conditions, has an IDLH (Immediately Dangerous to Life and Health) concentration of 20 ppm, which makes it an acute toxic hazard. Reducing the risk associated with an accidental release of sulfur trioxide involves identifying some of the potential causes of accidental releases that apply to the process facilities that manufacture or use sulfur trioxide. In this manual, examples of potential causes are identified as are specific measures thay may be taken to reduce the accidental release risk. Such measures include recommendations on plant design practices, prevention, protection and mitigation technologies, and operation and maintenance practices. Conceptual cost estimates of example prevention, protection, and mitigation measures are provided.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

Increasing concern about the potentially disastrous consequences of accidental releases of toxic chemicals resulted from the Bhopal, India, accident of December 3, 1984, which killed approximately 2,000 people and injured thousands more. A toxic cloud of methyl isocyanate was released. Concern about the safety of process facilities handling hazardous materials increased further after the accident at the Chernobyl nuclear power plant in the Soviet Union in April of 1986.

While headlines of these incidents have created awareness of toxic release problems, there have been other, perhaps less dramatic, incidents in the past. Interest in reducing the probability and consequences of accidental toxic chemical releases that might harm workers within a process facility and people in the surrounding community prompted the preparation of this manual and a series of companion manuals addressing accidental releases of toxic chemicals.

Historically, major incidents in the United States involving sulfur trioxide do not appear to have been common, although a release of sulfur trioxide in Baltimore, Maryland, in January 1978, caused respiratory injuries to 35 people (1).

1.2 PURPOSE OF THIS MANUAL

The purpose of this manual is to provide technical information about sulfur trioxide and specifically about prevention of accidental releases of

sulfur trioxide. The manual addresses technological and procedural issues, related to release prevention, associated with the storage, handling, and process operations involving sulfur trioxide as it is used in the United States. This manual does not address uses of sulfur trioxide not encountered in the United States.

This manual is intended as a summary for persons charged with reviewing and evaluating the potential for releases at facilities that use, store, handle, or manufacture sulfur trioxide. It is not intended as a specification manual, and in fact refers the reader to additional technical manuals and other information sources for more complete information on the topics discussed. Other information sources include manufacturers and distributors of sulfur trioxide, and technical literature on design, operation, and loss prevention in facilities handling toxic chemicals.

1.3 USES OF SULFUR TRIOXIDE

Sulfur trioxide (SO_3) is a commodity chemical, produced by the catalytic oxidation of sulfur dioxide (SO_2). In this work, data on the production of sulfur trioxide were not found, but based on the relative production of surfactants, a use of 300 million pounds per year of sulfur trioxide is estimated for recent years. Sulfur trioxide is primarily used as a sulfonating/sulfating agent to produce anionic surfactants. These include:

- Linear alkylbenzene sulfonates;
- Alcohol sulfates; and
- Alcohol ether sulfates.

Storage systems for liquid sulfur trioxide include 55-gallon drums and bulk storage tanks.

In addition to anhydrous sulfur trioxide, oleum (fuming sulfuric acid composed of sulfuric acid and sulfur trioxide) is also used. This manual focuses primarily on anhydrous sulfur trioxide, but some considerations also apply to oleum.

1.4 ORGANIZATION OF THE MANUAL

Following this introductory section, the remainder of this manual presents technical information on specific hazards and categories of hazards for sulfur trioxide and their control. These are examples only and are representative of only some of the hazards that may be related to accidental releases.

Section 2 discusses physical, chemical and toxicological properties of sulfur trioxide. Section 3 describes the types of facilities which manufacture and use sulfur trioxide in the United States. Section 4 discusses process hazards associated with these facilities. Hazard prevention and control are discussed in Section 5. Costs of example storage and process facilities reflecting different levels of control through alternative systems are also presented in Section 5. The examples are for illustration only and do not necessarily represent a satisfactory alternative control option in all cases. Section 6 presents a reference list. Appendix A is a glossary of key technical terms that might not be familiar to all users of the manual, and Appendix B presents selected conversion factors between metric (SI) and English measurement units.

SECTION 2

CHEMICAL CHARACTERISTICS

This section of the report describes the physical, chemical, and toxicological properties of sulfur trioxide as they relate to accidental release hazards.

2.1 PHYSICAL PROPERTIES

Anhydrous sulfur trioxide is a clear, colorless, oily liquid with a strong, acrid odor. Liquid sulfur trioxide freezes at temperatures around 90°F. Sulfur trioxide is hygroscopic and fumes upon exposure to moist air. Sulfur trioxide fumes combine with moisture in the air to form submicron sulfuric acid mist particles that are visible and form clouds of dense white fumes. Selected physical properties of sulfur trioxide are listed in Table 2-1.

Traces of water or sulfuric acid can catalyze the polymerization of liquid sulfur trioxide to solid forms that are difficult to remelt. Polymerization can be inhibited by adding various patented stabilizers to the liquid, such as 0.3% dimethylsulfate with 0.005% boric oxide (2). Sulfur trioxide can be absorbed in solutions of concentrated sulfuric acid; the resulting product is known in the U.S. as oleum. Because of the hygroscopic nature and high reactivity of sulfur trioxide, spills and leaks of liquid can result in hazardous releases of sulfuric acid mist to the atmosphere. In addition, since the vapor density of sulfur trioxide and sulfuric acid mist are greater than that of air, releases will remain close to the ground and could create a potentially dangerous situation for workers and surrounding communities. Sulfuric acid mist forms an opaque, white, dense cloud that resists dispersal and has been used as a smoke screen (3). This opaque "smoke" obscures vision

TABLE 2-1. PHYSICAL PROPERTIES OF SULFUR TRIOXIDE

		Reference
CAS Registry Number	7446-11-9	
Chemical Formula	SO_3	
Molecular Weight	80.06	
Normal Boiling Point	112.6°F @ 14.7 psia	4
Melting Point (γ-phase)	62.2°F	4
Liquid Specific Gravity (H_2O=1)	1.84 @ 100°F	7
Vapor Specific Gravity (air=1)	2.8 @ 68°F	7
Vapor Pressure	5.41 psia @ 77°F	7
Vapor Pressure Equation		4

$$\log P_v = A - \frac{B}{T+C}$$

where: P_v = vapor pressure, mm Hg
T = temperature °F ($60 < T < 160$)
A = 7.8663, a constant
B = 2086, a constant
C = 306.4, a constant

Liquid Viscosity	1.30 centipoise @ 100°F	5
Solubility in Water	Complete*	7
Specific Heat at Constant Pressure (vapor)	0.19 Btu/(lb-°F) @ 212°F	5
Specific Heat at Constant Pressure (liquid)	0.77 Btu/(lb-°F) @ 100°F	5
Latent Heat of Vaporization	235.3 Btu/lb @ 112.6°F	5
Heat of Dilution	907 Btu/lb	6

* Reacts violently with water.

(Continued)

TABLE 2-1. (Continued)

		Reference
Coefficient of Thermal Expansion	0.00111 per °F @ 64°F	2
Additional Properties Useful in Determining Other Properties from Physical Property Correlations:		
Critical Temperature	424.9 °F	4
Critical Pressure	1232 psia	4
Critical Density	39.49 lb/ft^3	4

and makes visual identification of the source of a leak of sulfur trioxide or the volume involved, difficult; this can hamper efforts to control a leak or spill.

Liquid sulfur trioxide has a large coefficient of thermal expansion. As a result, liquid-full equipment is a special hazard. A liquid-full vessel is a vessel that is not vented and is filled with liquid sulfur trioxide with little or no vapor space present above the liquid. A liquid-full line is a section of pipe that is sealed off at both ends and is full of liquid sulfur trioxide with little or no vapor space. In these situations, there is no room for thermal expansion of the liquid, and temperature increases can result in containment failure.

2.2 CHEMICAL PROPERTIES AND REACTIVITY

Sulfur trioxide is a highly reactive chemical. The most significant chemical properties contributing to the potential for releases are as follows:

- Anhydrous sulfur trioxide combines with moisture in the air to form sulfuric acid mist. Sulfuric acid mist consists of visible submicron particles that form a dense white cloud. Sulfuric acid mist is corrosive to most metals such as cast iron, steel, copper, copper alloys, and aluminum. The mist is also an extreme inhalation hazard.

- Sulfur trioxide can solidify at temperatures at or below 90°F. Trace amounts of water or sulfuric acid can catalyze the formation of solid sulfur trioxide. Solid sulfur trioxide can exist in three trimorphic phases: gamma (γ, mp = 62.2°F), beta (β, mp = 90.5°F), and alpha (α, mp = 144°F). The α-phase is the most stable, and both α- and β- forms melt to give liquid γ-sulfur trioxide. Once solid polymeric (frozen) sulfur trioxide has formed, higher temperatures (122-167°F)

are required to fully convert the polymers back to liquid monomer. Since the liquid γ-phase has a normal boiling point of 112°F, it can rapidly vaporize at temperatures required to melt the α-sulfur trioxide. Due to the sudden increase in vapor pressure, there is a risk of overpressure and rupture of containers and vessels.

- Considerable heat is evolved when sulfur trioxide or oleum is diluted with water. Violent reactions can result from the inappropriate addition of water or caustic solutions to these materials.

- Anhydrous sulfur trioxide attacks cast iron, copper and copper alloys, silver, tantalum, titanium, zirconium, neoprene, polypropylene, and fluoroelastomers. With the addition of water, it can behave like oleum, and in the presence of sufficient water, like sulfuric acid, with attendant corrosive effects on cast iron, mild steel, stainless steels, most copper and nickel alloys, and aluminum. No elastomer has been found that is non-reactive with sulfur trioxide (5). Both fluorinated synthetic rubbers and polytetrafluoroethylene are reportedly resistant to sulfur trioxide (5).

- Anhydrous sulfur trioxide reacts exothermically with organic materials, and may cause ignition when in contact with combustible materials such as sawdust or oily rags.

- Anhydrous sulfur trioxide reacts with cyanides and sulfides to produce toxic hydrogen cyanide and hydrogen sulfide, respectively. In addition to the toxicity hazard of these gases, this can result in potentially explosive mixtures in confined areas, since both hydrogen cyanide and hydrogen sulfide are flammable.

2.3 TOXICOLOGICAL AND HEALTH EFFECTS

Sulfur trioxide is highly toxic, and is a highly corrosive and severe irritant to the skin, eyes, and respiratory system. It rapidly dehydrates body tissues and causes severe burns. The effects of exposure to sulfur trioxide in the liquid or vapor form are not well documented. The inhalation of dry sulfur trioxide fumes in a confined area will cause immediate destruction of the lungs and upper respiratory tract. If swallowed, liquid sulfur trioxide will cause immediate destruction of the tissues of the mouth and esophagus. Contact with the eyes may result in a total loss of vision. Table 2-2 reports the lowest published concentration for toxic effects (TC_{LO}) of sulfur trioxide by inhalation.

Exposure limits for sulfur trioxide have not been established by OSHA or ACGIH. However, since sulfur trioxide reacts rapidly with moisture in the air to form sulfuric acid mist, exposure limits for sulfuric acid mist are interpreted as including sulfur trioxide. The Permissible Exposure Limit (PEL) for sulfuric acid mist (and hence, sulfur trioxide) is reported in Table 2-2. Inhalation of the mist, while much less hazardous than pure sulfur trioxide, is strongly irritating and may cause permanent lung damage.

Initial effects of human overexposure to sulfuric acid mist include: eye corrosion with corneal or conjunctival ulcerations; skin burns or ulceration; irritation of the upper respiratory passages; temporary lung irritation effects with cough, discomfort, difficult breathing, or shortness of breath; or damage to tooth enamel. Exposure to higher levels may cause severe lung damage; the lung injury may be delayed. There are no reports of human sensitization. Individuals with preexisting diseases of the lungs may have increased susceptibility to the toxicity of excessive exposures. Table 2-3 presents a summary of predicted human health effects of exposure to various concentrations of sulfuric acid aerosols.

TABLE 2-2. EXPOSURE LIMITS FOR SULFUR TRIOXIDE/SULFURIC ACID MIST

Exposure Limit	Concentration (ppm)	Description	Reference
IDLH	20[a]	The concentration defined as posing an immediate danger to life and health (i.e. causes toxic effects for a 30-minute exposure).	7
PEL	0.3[a]	A time-weighted 8-hour exposure to this concentration, as set by the Occupational Safety and Health Administration (OSHA), should result in no adverse effects for the average worker.	7
TC_{LO}	9[b]	This concentration is the lowest published concentration causing toxic effects (irritation) for a 1-minute exposure.	8

[a] Exposure limit for sulfuric acid mist.
[b] TC_{LO} for sulfur trioxide.

TABLE 2-3. PREDICTED HUMAN HEALTH EFFECTS OF EXPOSURE TO VARIOUS CONCENTRATIONS OF SULFURIC ACID AEROSOLS

mg H_2SO_4/m^3	Predicted Effect
0.5 - 2.0	barely noticeable irritant
3.0 - 4.0	coughing, easily noticeable
6.0 - 8.0	decidely unpleasant, marked alterations in respiration

Source: Reference 2.

SECTION 3

PROCESS FACILITY DESCRIPTIONS

This section briefly describes the manufacture and uses of sulfur trioxide in the United States. Major hazards of these processes associated with accidental releases are discussed in Section 4. Preventive measures associated with these hazards are discussed in Section 5.

3.1 SULFUR TRIOXIDE MANUFACTURE

Sulfur trioxide is manufactured by the catalytic conversion of sulfur dioxide gas. The sulfur trioxide can either be used directly after conversion (in sulfonation plants using a sulfur burner with a converter), or it can be absorbed into weak sulfuric acid or oleum for manufacture of concentrated sulfuric acid, oleum, or liquid sulfur trioxide (using the "contact process"). Liquid sulfur trioxide is obtained by the distillation of strong oleums.

Figure 3-1 illustrates the contact process for a double-absorption sulfur-burning plant producing sulfuric acid, oleum, and liquid sulfur trioxide. The double-absorption plant uses an intermediate absorption step to improve overall sulfur dioxide conversions to 99.5-99.8%.

There are several sources of sulfur-containing raw materials. These include spent/waste sulfuric acid, hydrogen sulfide (H_2S), and most commonly, liquid elemental sulfur. Regardless of the source of sulfur, the first step in the manufacture of sulfur trioxide is the production of a continuous, contaminant-free gas stream containing appreciable amounts of sulfur dioxide and some oxygen. The sulfur dioxide rich gas stream is then passed over a vanadium oxide catalyst to form sulfur trioxide gas. The sulfur trioxide gas is subsequently cooled before use in sulfonation plants, or before entering a

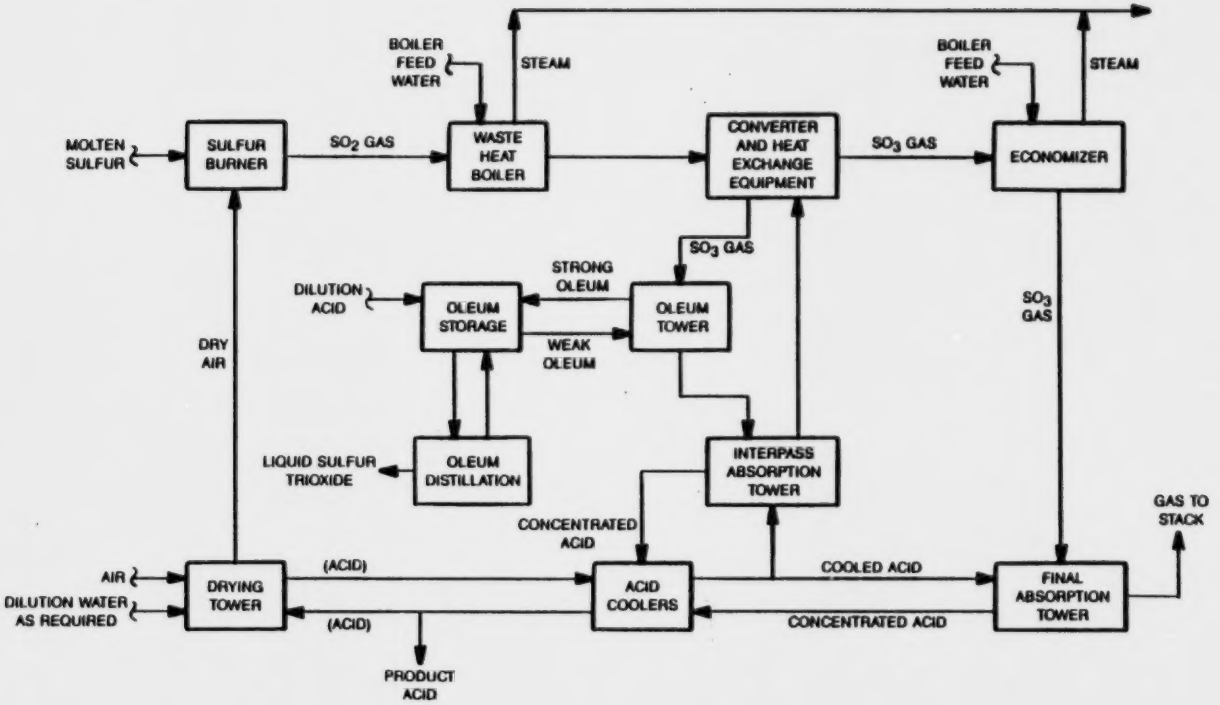

Figure 3-1. Conceptual diagram of typical sulfur trioxide manufacturing process.

Source: Adapted from Reference 2.

series of absorption towers which are part of the contact process. A dry gas stream entering the catalytic converters is desirable; the air used for burning elemental sulfur is generally pre-dried, while other processes dry the sulfur dioxide stream after it leaves the combustion chamber. The gas leaving the converter typically contains about 10 volume percent sulfur trioxide, with the balance being dry air.

Plants producing oleum or liquid sulfur trioxide are different from those producing only sulfuric acid since they have one or two additional packed towers irrigated with oleum ahead of the normal sulfur trioxide absorption towers. The absorption towers are typically carbon steel vessels lined with acid-proof brick and mortar and packed with ceramic rings or saddles. Partial absorption of sulfur trioxide occurs in these towers and sulfuric acid is added to maintain the desired oleum concentration. Because of the high sulfur trioxide vapor pressure of high-concentration oleums, only 30-60% of the sulfur trioxide present in the product gas is absorbed in the oleum tower. The remaining sulfur trioxide is absorbed by concentrated (98-99%) sulfuric acid.

Liquid sulfur trioxide is obtained by heating oleum in a steel boiler to generate sulfur trioxide vapor, which is then condensed. Oleums with greater than 40% free sulfur trioxide are made by mixing sulfur trioxide with low-concentration oleums.

High hazard areas in the manufacturing process, excluding bulk storage and transfer (discussed in Section 3.4) include the following:

- Feed treatment to remove water;
- Converter;
- Sulfur trioxide cooler;
- Absorbers;
- Oleum boiler;
- Sulfur trioxide condenser; and
- Oleum mixing.

The feed treatment process to remove water is a critical area of the process because water and sulfur trioxide combine to form sulfuric acid which rapidly corrodes many materials of construction. A properly designed system should use materials of construction which take this corrosion potential into account. Deficiencies or failures in the drying tower could lead to a protracted corrosion problem resulting eventually in equipment failure.

Because of the exothermic nature of the oxidation of sulfur dioxide to sulfur trioxide, there is the potential for overheating resulting in overpressure in the catalytic converter. This could lead to subsequent equipment failure and loss of containment.

The sulfur trioxide cooler on the converter outlet stream contains a dilute gaseous stream of sulfur trioxide. However, failure of the tubing in the heat exchanger could result in a leak into the cooling water system, leading to sulfuric acid formation and a potential corrosion problem.

A loss of liquid flow to any of the absorption towers would result in a buildup of sulfur trioxide gas leading to overpressure and a potential release. Insufficient cooling of the liquid absorber feed could also lead to overtemperature and overpressure since the absorption of sulfur trioxide in an exothermic process.

The heater for the oleum boiler may be a steam-heated jacket, tube bundle, or coil. Failure of the jacket or tubing could result in a violent reaction between the steam and oleum in the reboiler. This could lead to rupture of the boiler and a direct release of oleum and/or sulfur trioxide. Also, failure of the temperature control system could result in overheating which would cause an overpressure of the boiler and a possible release.

The water-cooled condenser for condensing liquid sulfur trioxide presents the possibility of a leak into the cooling water system, leading to sulfuric acid formation and a potential corrosion problem.

The oleum mixing units are used to strengthen sulfuric acid or oleum. They require a supply of liquid or vaporized sulfur trioxide and must be equipped for flow control. Failure of the flow control system could result in excessive sulfur trioxide feed, leading to overpressure and a possible direct release of oleum or sulfur trioxide.

3.2 SULFUR TRIOXIDE CONSUMPTION

The primary use of sulfur trioxide in the United States is for the sulfonation or sulfation of organic compounds. Table 3-1 presents a listing of some of the chemicals produced and their end uses. This subsection summarizes the major technical features, related to release hazards, of typical processing facilities found in the United States.

Although the terms sulfonation and sulfation are often used interchangeably, they differ chemically. Sulfonation involves the addition of an SO_3 group into an organic molecule to form a sulfonate; either a sulfuric acid ($-SO_3H$), a salt ($-SO_3Na$), or a sulfonyl halide ($-SO_3X$). Sulfation, on the other hand, involves the introduction of an SO_3 group into an organic molecule to form a sulfate with the characteristic $-OSO_3-$ configuration.

Probably the largest use of liquid sulfur trioxide is for the sulfonation of dodecylbenzene to produce dodecylbenzene sulfonate. This material is widely used in industrial detergents and is highly biodegradable under anaerobic conditions. Also, alkyl sulfates are produced by sulfation of long chain primary alcohols using sulfur trioxide. These products are useful as detergent powders in dishwashing formulations, and as shampoo ingredients.

A block diagram of a typical sulfur trioxide sulfonation/sulfation process is shown in Figure 3-2. This is one of several possible configurations (9,10,11). The processes differ primarily in the configuration of the reactor unit. These reactors employ continuous falling-film sulfonation. The gaseous sulfur trioxide is diluted with dry air or nitrogen to a concentration of 4 to

TABLE 3-1. TYPICAL SULFONATED/SULFATED PRODUCTS MANUFACTURED FROM SULFUR TRIOXIDE AND ORGANIC FEEDSTOCKS

Reactant (example)	End Product (example)	Uses
Alkylated benzene from straight chain normal paraffins (dodecylbenzene)	Alkyl aryl sulfonates (dodecylbenzene sulfonate)	Industrial detergents
Long chain primary alcohols (lauryl alcohol)	Alkyl sulfates (sodium lauryl sulfate)	Shampoo, dishwashing powder
Fats and oils (lard; castor, soybean, or peanut oil)	Sulfonated fats and oils	Wetting agents, detergents, emulsifiers
Alpha olefins	Alpha-olefin sulfonates	Personal care/ household products
Ethoxylated alcohols	Ethoxylated alcohol sulfates	Detergents, emulsifiers
Petroleum products (topped crude oil)	Petroleum sulfonates	Tertiary oil recovery
Linear polystyrene	Linear water soluble sulfonated polystyrenes	Ion exchange resins
Substituted benzenes	Sulfonated alkyl benzenes	Intermediates for dyes, drugs, and insecticides
Long-chain alkylated benzenes	Oil soluble sulfonates	Lubricant additives, emulsifiers, rust preventives

Source: References 2 and 5.

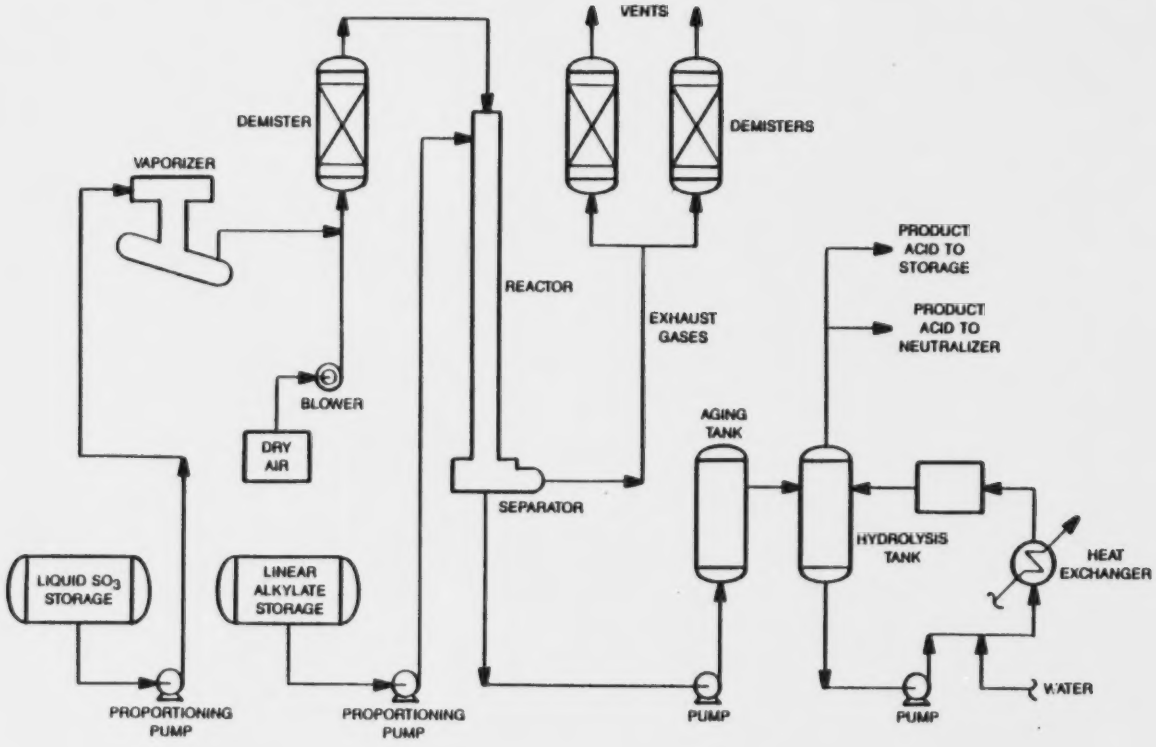

Figure 3-2. Conceptual process flow diagram of typical continuous sulfur trioxide film sulfonation process.

Source: Adapted from Reference 2.

10 vol% sulfur trioxide. The gas feed rate is matched to the liquid (organic) feed for essentially complete reaction. The reaction occurs at atmospheric pressure and between 85 and 144°F. The gaseous residence time is very short (order-of-magnitude <0.2 sec), and the gas-liquid contact is turbulent for complete mixing. The reactor is cooled with cooling water to remove the heat of reaction.

The source of sulfur trioxide gas can either be a sulfur burner/converter, or liquid sulfur trioxide vaporized before dilution with air. According to one sulfonation equipment vendor (12), nearly all new sulfonation plants employ the sulfur burner/converter as a source of sulfur trioxide. However, many older existing plants may still use liquid sulfur trioxide. Liquid sulfur trioxide is delivered to the vaporizer by a proportioning pump to maintain the proper ratio of sulfur trioxide to organic feed.

Upon leaving the reactor, liquid sulfonic acid product is separated from the effluent or spent gas in a liquid separator or cyclone. The liquid sulfonic acid is then subjected to further downstream processing (for example, aging/digestion, hydrolysis, or neutralization). The effluent gas, consisting of particulate-laden air (entrained liquid sulfonic acid droplets) and small amounts of unreacted sulfur trioxide, is sent through demisters or scrubbers for cleanup before venting.

From a sulfur trioxide release perspective, a fundamental characteristic of the sulfonation process is the use of sulfur trioxide as a reactant. Because of the high reactivity of pure sulfur trioxide, it is diluted with dry air or nitrogen.

High hazard areas in the sulfonation process, excluding bulk storage and transfer (discussed in 3.4), include the following:

- Liquid sulfur trioxide proportioning pump;
- Vaporizer to convert liquid sulfur trioxide to vapor; and
- Reactor.

The above mentioned hazard areas apply to sulfonation processes using liquid sulfur trioxide. Sulfonation processes using a sulfur-burner and converter would have the same hazards as noted earlier in Section 3.1 for production of gaseous sulfur trioxide (converter and cooler), in addition to the reactor. However, neither the liquid sulfur trioxide proportioning pump nor the vaporizer would be included.

Failure of the flow control on the liquid sulfur trioxide proportioning pump could result in excess sulfur trioxide being fed to the reactor. This may cause overpressurization of the reactor or unreacted sulfur trioxide could cause a downstream process upset. This could result in either overpressurization or emergency venting; if the scrubber on the reactor vent line is either not properly sized or not operating, a direct release of sulfur trioxide could result.

The liquid sulfur trioxide vaporizer must be equipped with temperature controls to prevent unintentional cooling and resultant solidification of the liquid sulfur trioxide. Remelting of solidified sulfur trioxide can result in excessive pressure increases which may cause a rupture in the vessel. Also, failure of the steam jacket or tubing could result in a violent reaction between the steam and liquid sulfur trioxide in the vaporizer. This could lead to rupture of the vaporizer and a direct release of sulfur trioxide.

The reactor must be equipped with controls and monitors for temperature and pressure. Temperature must be regulated to prevent cooling and solidification of sulfur trioxide.

Pressure must be monitored to avoid emergency venting. A loss of cooling could result in increased temperature and potential overpressure. Also, a loss of air flow to the reactor could result in a concentrated sulfur trioxide feed stream. Since the reaction occurs immediately and exothermically, there is the potential for a runaway reaction if the cooling capacity cannot handle the excess load at the entrance section of the reactor.

3.3 STORAGE AND TRANSFER

Sulfur trioxide is difficult to store because of its high freezing point. It is necessary to maintain the sulfur trioxide at 95 to 105°F and to exclude even trace quantities of water, sulfuric acid or other impurities to avoid polymerization to solid, high-melting forms (see Subsection 2.1). Liquid sulfur trioxide is sold in both stabilized and unstabilized forms. The stabilized form is more resistant to polymerization.

Sulfur trioxide is shipped in drums, in tank trucks, and tank cars (13). Figures 3-3 and 3-4 show typical storage and transfer systems. These figures are only conceptual representations of typical storage and transfer systems. Actual systems will vary in the design and method of storage and transfer.

Storage tanks may be located indoors within a temperature-controlled hot room. Alternatively, storage tanks may be located outdoors if kept heated and well insulated. Under no circumstances should storage tanks have internal steam coils due to the risk of tube failure and potential violent reaction or explosion (4).

All sulfur trioxide lines should either be heat traced and insulated, or located within the hot room. This is also true for valves, pumps, metering devices, vaporizers, and other associated equipment. If heat tracing is used, there should be a 1/4-inch thick insulation layer between the heat trace and the sulfur trioxide line to prevent localized overheating ("hot spots") (13). Since liquid sulfur trioxide freezes at 90°F, it is crucial that all transfer lines be kept heated to prevent solidification of sulfur trioxide. If a transfer line were to become blocked due to solidification, stagnation could result in overheating or over-pressurization of pumps, or render shut-off valves inoperative.

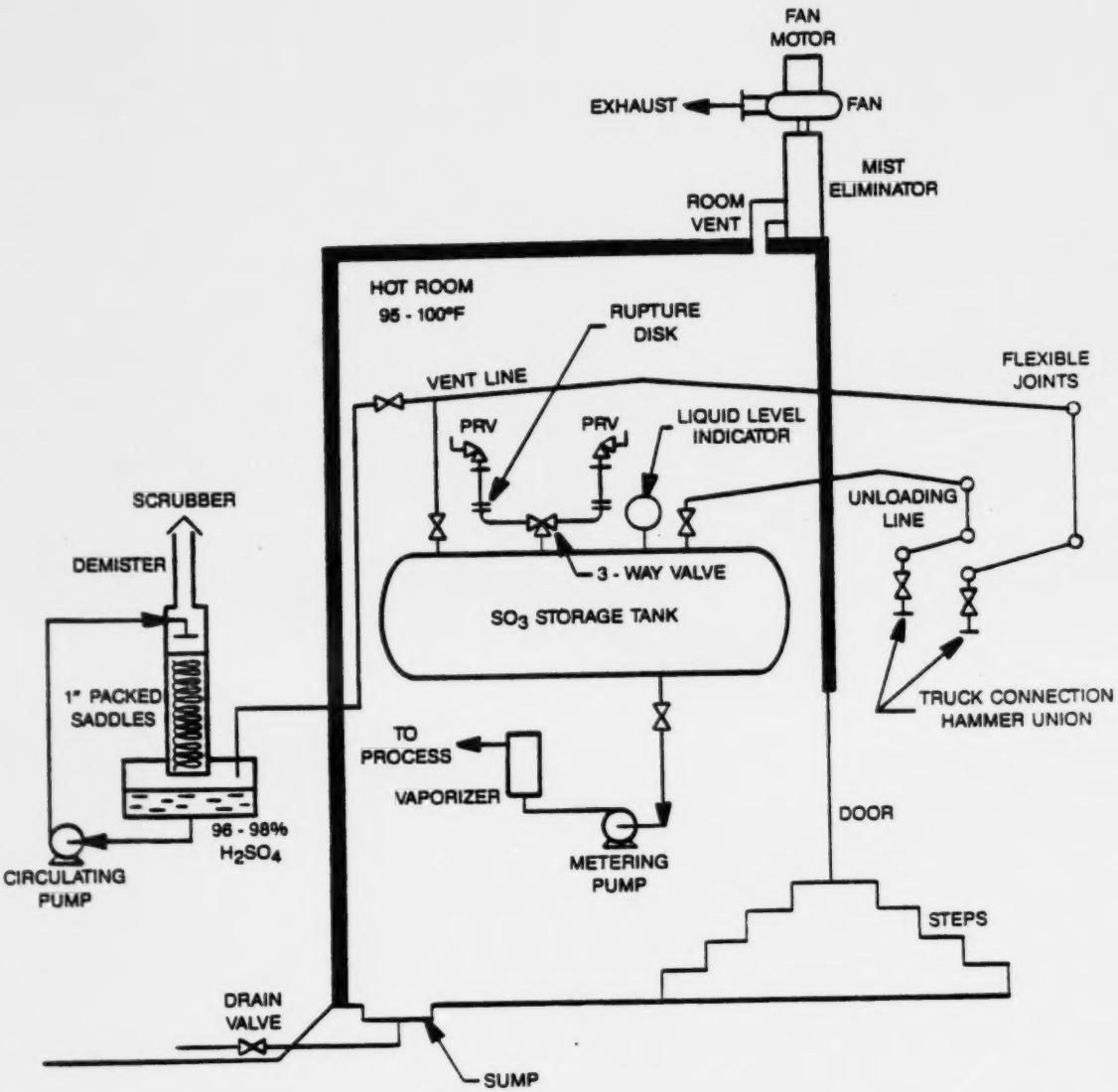

Figure 3-3. Conceptual diagram of typical liquid sulfur trioxide storage system.

Source: Adapted from Reference 4.

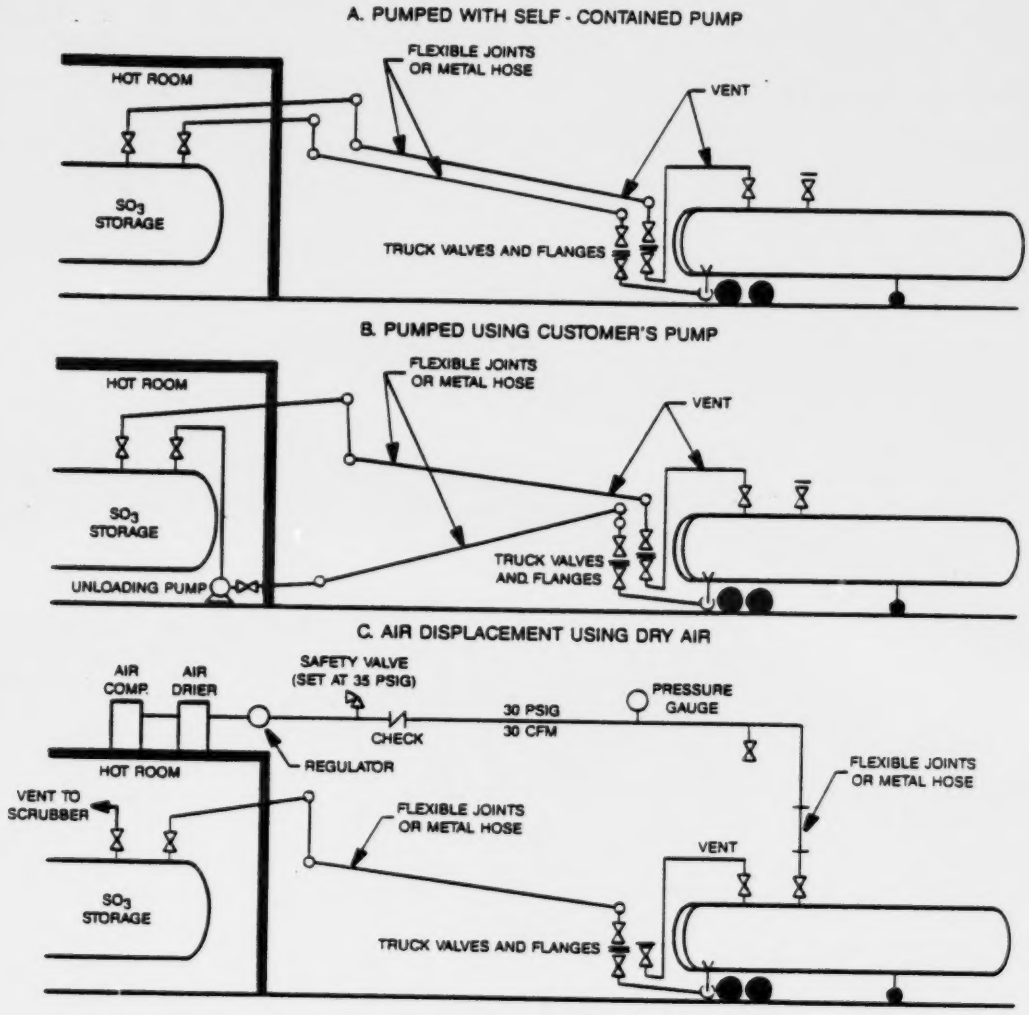

Figure 3-4. Conceptual diagram of typical liquid sulfur trioxide transfer systems.

Source: Adapted from Reference 4.

Transfer of the sulfur trioxide to storage is accomplished using either pumps or compressed gas pressure. Typically, compressed air is dried to a minimum dewpoint of -40°F, and cleaned to remove oil and foreign matter before being used to pressure the sulfur trioxide source vessel (5). A vent line from the storage tank is commonly connected to a scrubber or mist eliminator. The scrubber is designed to prevent the release of sulfuric acid mist when the transfer is occurring. When pump transfer is performed, a closed loop between the storage tank and the tank car is commonly used. The closed loop allows for collection of the displaced sulfur trioxide vapors and prevents release to the atmosphere.

The fume scrubber system consists of a packed absorption tower or mist eliminator and an acid or water tank. It is used to control sulfur trioxide vapors from the vent of storage tanks.

It should be mentioned that if solid (frozen) sulfur trioxide is formed, it is possible to remelt the solid by careful heating. The remelting of solid sulfur trioxide is a hazardous procedure. The formation of solid sulfur trioxide is inhibited or minimized when using stabilized liquid sulfur trioxide. However, with pure, unstabilized sulfur trioxide, a solid can form that is difficult to remelt at normal storage temperatures (i.e., between 95 and 105°F).

Sometimes shipments of sulfur trioxide are received in drums, but the contents are frozen. The best way to recover the liquid sulfur trioxide is to place the sealed, frozen drum(s) in a hot room at 95 to 105°F for several days. If solid material is found in drums maintained at recommended storage temperatures due to the presence of the higher melting α-phase solid sulfur trioxide, the temperatures can be raised to 109°F. With pure, unstabilized sulfur trioxide, higher temperatures may be required to melt the solid. However, since the γ-phase sulfur trioxide boils at 112.6°F, when the solid eventually does melt, it is to the liquid phase above its normal boiling point.

Thus, the superheated liquid is vaporized, resulting in a large pressure increase (the so-called "alpha explosion"). The pressure increase has enough force and is sudden enough to shatter glass containers or rupture drums, causing a direct release of sulfur trioxide.

All storage tanks should be equipped with level controls to prevent overfilling and spillage. A closed loop recirculation line is often used to provide a means for mixing the tank contents.

SECTION 4

PROCESS HAZARDS

Some of the specific process hazards associated with the manufacture and uses of sulfur trioxide were cited in the previous sections of this manual. This section presents some examples of more general causes of releases which may be common to any sulfur trioxide process.

Sulfur trioxide can be used safely in appropriate processing and storage equipment. However, when exposed to the atmosphere, sulfur trioxide combines with moisture in the air to form sulfuric acid mist. This acid mist can be detected in air by its white fumes, pungent odor and irritant property.

Sulfur trioxide releases can originate from many sources including leaks or ruptures in vessels, piping, valves, instrumentation connections, and process machinery such as pumps and compressors. In addition, losses may occur through leaks at joints and connections such as flanges, valves, and fittings where failure of gaskets or packing might occur.

Potential sulfur trioxide releases may be liquid or vapor. Liquid spills can occur when sulfur trioxide is at or below its boiling point of 112°F or when a sudden release of sulfur trioxide above this temperature results in evaporative cooling of the remaining liquid by vapor flashing. Direct releases of vapor also can occur from the vapor spaces of containers or lines containing the vapor. Liquid spills of oleum can release some sulfur trioxide as well. However, the vapor pressure of sulfur trioxide in oleum is considerably less than the vapor pressure of pure sulfur trioxide. Nonetheless, the threat from oleum should not be discounted, especially if spills occur on hot surfaces where evaporation rates are high.

4.1 POTENTIAL CAUSES OF RELEASES

Failures leading to accidental releases may be broadly classified as due to process, equipment, or operational causes. This classification is for convenience only. Causes discussed below are examples only and do not necessarily include all possibilities. A more detailed discussion of possible causes of accidental releases is presented in a companion manual on control technologies in the prevention reference manual series of which this present manual is a part (14).

4.1.1 Process Causes

Process causes are related to the fundamentals of process chemistry, control, and general operation. Examples of process causes of a sulfur trioxide release include:

- Excess sulfur trioxide or organic feed to a sulfonation/sulfation reactor leading to excessive exothermic reaction, combined with failure of the cooling system;

- Backflow of process reactants to a sulfur trioxide feed tank;

- Inadequate water removal from organic feeds to the sulfonation/sulfation process or feeds to the sulfur trioxide converter over a long period of time leading to progressive corrosion;

- Excess feeds in any part of the system leading to overfilling or overpressuring equipment;

- Loss of liquid flow to sulfur trioxide absorbers leading to overpressure and overtemperature;

- Loss of temperature control in cooling units (e.g., reactor or condenser) or heating units (e.g., vaporizer); and

- Overpressure in sulfur trioxide storage vessels due to overheating or overfilling. These situations may be caused by exothermic reactions from contamination, fire exposure, or unrelieved overfilling.

4.1.2 Equipment Causes

Equipment causes of accidental releases result from hardware failures. Some possible causes include:

- Failure of vessels at normal operating conditions due to weakening of equipment from excessive stress, or corrosion; excessive stress can be caused by improper fabrication, construction, installation, or external loadings;

- Overheating, especially for sulfonation reactors or sulfur trioxide vaporizers;

- Mechanical fatigue and shock in any equipment. Mechanical fatigue could result from age, vibration, or stress cycling, caused by pressure cycling, for example. Shock could occur from collisions with moving equipment such as cranes, or other equipment in process or storage areas;

- Thermal fatigue and shock in sulfonation reactors or heat exchangers;

- Brittle fracture in any equipment, but especially in carbon steel equipment subjected to extensive corrosion where hydrogen embrittlement from hydrogen release by sulfuric acid attack may have occurred. Equipment constructed of high alloys, especially high strength alloys selected to reduce the weight of major process equipment, might be especially sensitive where some corrosion has occurred, or severe operating conditions are encountered;

- Creep failure in equipment subjected to extreme operational upsets, especially excess temperatures. This can occur in equipment subjected to a fire, for example; and

- All forms of corrosion. For example, external corrosion from fugitive emissions of sulfuric acid mist could lead to equipment weakening.

4.1.3 Operational Causes

Operational causes of accidental releases are a result of incorrect operating and maintenance procedures or human errors (i.e., not following correct procedures). These causes include:

- Overfilled storage vessels due to lack of attention, failure to shutoff flow, or failure to note a partially full vessel before adding more material;

- Improper process system operation such as failure to make proper connections and failure to close a valve when disconnecting a hose line;

- Errors in loading and unloading procedures;

- Inadequate maintenance in general, but especially on water removal unit operations, and pressure relief systems and other preventive and protective systems;

- Lack of inspection and non-destructive testing of vessels and piping to detect corrosion weakening; and

- Incomplete knowledge of the properties of a specific chemical, chemical system, or process leading to unexpected corrosion or chemical reactions that could cause excessive heat or pressure.

SECTION 5

HAZARD PREVENTION AND CONTROL

5.1 BACKGROUND

Prevention of accidental releases relies on a combination of technological, administrative, and operational practices. These practices apply to the design, construction, and operation of facilities where sulfur trioxide is stored and used. Considerations in these areas can be grouped as follows:

- Process design;
- Physical plant design;
- Operating and maintenance practices; and
- Protective systems.

In each of these areas, attention must be given to specific factors that could lead to a process upset or failure which could directly cause a release of sulfur trioxide to the environment, or result in an equipment failure which would then cause the release. At a minimum, equipment and procedures should be in accordance with applicable codes, standards, and regulations. In addition, stricter equipment and procedural specifications should be in place if extra protection against a release is considered appropriate (i.e., as determined by a hazard assessment).

The following subsections discuss some specific aspects of the above areas as they relate to release prevention. In addition, illustrative cost estimates for different levels of control applied to storage and process facilities are also included. More detailed discussions can be found in the manual on control technologies, part of this prevention reference manual series (14).

5.2 PROCESS DESIGN

Process design involves the fundamental characteristics of processes which use sulfur trioxide. This includes an evaluation of how deviations from intended process design features might initiate a series of events that could result in an accidental release. The primary focus is on how the process is controlled in terms of the basic process chemistry and the variables of flow, pressure, temperature, composition, and quantity. Additional considerations may include mixing systems, fire protection, and process control instrumentation. Modifications to enhance process integrity may result from a review of these factors and could involve changes in quantities of materials, process pressures and temperatures, the unit operations, the sequence of operations, the process control strategies, and the instrumentation.

Table 5-1 shows the relationship between some process design considerations and individual processes described in Section 3 of this manual. This does not mean that other factors should be ignored, nor does it mean that proper attention to just the considerations in the table ensures a safe system. However, the items listed, and perhaps others, must be properly addressed if a system is to be safe.

The most significant considerations are aimed at preventing overheating and overpressuring systems containing sulfur trioxide. If sulfur trioxide is fed from a storage vessel under its own vapor pressure, the primary means of overpressure would be from overheating. Where sulfur trioxide is fed by nitrogen padding of a storage vessel, or through pumps, overpressuring could occur without overheating. Equipment failure without overpressure is possible if corrosion has weakened process equipment. Temperature monitoring is important, not only because of a potential overpressure or equipment weakening due to overheating, but also because sulfur trioxide's corrosiveness increases with temperature and solidifies to a difficult melting form at relatively high temperatures.

TABLE 5-1. EXAMPLES OF PROCESS DESIGN CONSIDERATIONS FOR PROCESSES INVOLVING SULFUR TRIOXIDE

Process Design Consideration	Process or Unit Operation
Contamination (with water especially)	All
Flow control of sulfur trioxide feed	All
Temperature sensing and cooling medium flow control	Sulfonation/sulfation reactors
Adequate pressure relief	Storage tanks, reactors, heat exchangers
Corrosion monitoring	All, but especially recycle circuits
Temperature monitoring	All reactors, storage tanks, vaporizers
Level sensing and control	Storage tanks

5.3 PHYSICAL PLANT DESIGN

Physical plant design considerations include equipment, siting and layout, and transfer/transport facilities. Vessels, piping and valves, process machinery, instrumentation, and factors such as location of systems and equipment must all be considered. The following subsections cover various aspects of physical plant design beginning with a discussion of materials of construction. This section is not intended to provide detailed specifications for the design of a facility handling sulfur trioxide. The discussion is intended to be illustrative examples of some of the kinds of considerations that are required in the design of the physical facilities to minimize the chance of a sulfur trioxide release.

5.3.1 Equipment

Materials of Construction--

The proper selection of materials of construction for sulfur trioxide service is dictated by conditions which directly and indirectly affect corrosion. Temperature, pressure, moisture content, flow velocity, aeration, and impurities such as water or sulfuric acid are important considerations in determining the appropriate materials. Table 5-2 presents a list of possible materials of construction for sulfur trioxide service.

Mild steel is generally satisfactory for storage and handling of sulfur trioxide and oleum (4, 13, 15, 16). In the absence of moisture, the rate of corrosion is very slow (0.25 mil/yr at 86°F) (13). Sulfur trioxide spilled on the exterior surface of the tank can become extremely corrosive as acid becomes diluted with atmospheric moisture or rain water. For improved corrosion resistance, 304 stainless steel can be used (4,13).

Schedule 80 carbon steel pipe with welded flanged connections is commonly used for sulfur trioxide service (13). However, 304 stainless tubing with welded joints is desirable for use in the hot room environment, where its lack of maintenance requirements is a benefit (4,13).

TABLE 5-2. MATERIALS OF CONSTRUCTION FOR SULFUR TRIOXIDE SERVICE

Satisfactory

Metals	Non Metals
Carbon steel*	Fluorocarbons (polytetrafluoroethylene)
Stainless Alloy 20**	Fluorinated synthetic rubbers
302/304/321/347 Stainless Steels**	Polychlorotrifluoroethylene
316/317 Stainless Steels**	
Hastelloy C	
Monel	
Ni-resist Iron	
Gold	

Unsatisfactory

Metals	Non Metals
Cast Iron	Neoprene
Brass, Bronze, and Copper	Styrene-butadiene rubbers
Silver	Polypropylene
Tantalum	Polyvinylidenefluoride
Titanium	
Zirconium	

* Acceptable as long as sulfuric acid content is less than 0.1%; recommended for piping and storage tanks.

** Recommended for pumps, valves, and areas of turbulence.

Source: References 4, 13, 15, and 16.

For pumps, valves, and other areas of turbulence, stainless Alloy 20, 304 SS, or 316 SS are commonly used (4). Gaskets or packing should be made of polytetrafluoroethylene, polychlorotrifluoroethylene, or other fluorocarbon (4). Gaskets should be the envelope type, either encapsulated or restrained with mesh (4).

Vessels--

A variety of storage and process vessels are used in sulfur trioxide service. Examples include small storage cylinders, chemical reactors, absorption columns, heat exchangers, and large storage tanks. Each type of vessel has certain specifications under various codes and standards which are supposed to be adhered to in design and fabrication.

Sulfur trioxide storage vessels range in size from 3 gallon drums for sample quantities up to several thousand gallon storage tanks used by producers. The shell of a tank inside a hot room does not need to be covered, and thus the exterior surface can be easily inspected. This is one reason most users of sulfur trioxide prefer to use hot room storage in place of outdoor storage. The hazard associated with enclosed sulfur trioxide storage is felt to be more than offset by the ability to regularly inspect the tank and maintain the proper temperature. As a result of the relatively large inventories contained in sulfur trioxide storage vessels, they represent one of the most hazardous areas of a sulfur trioxide process facility.

In general, sulfur trioxide storage tanks should be designed and built in accordance with the ASME Code for Unfired Pressure Vessels. Special considerations may be as discussed in the code for lethal materials, or even stricter standards may be appropriate. A pressure vessel capable of handling 50 psig has been recommended by one vendor since this rating makes it possible to melt the high melting α-phase with the resulting vapor pressure of 23 psig (4).

As stated earlier, the usual material for sulfur trioxide storage vessels is mild steel. Because of the potential release of hydrogen during corrosive attack by sulfuric acid mist, welding processes are usually carefully

controlled to avoid heat-affected zone hardness which can lead to hydrogen stress cracking. Shielded arc welding with double butt-welded longitudinal seams and single butt-welded girth seams with seal welds on the inside is commonly used for vessels, including those in sulfur trioxide service.

Vessel nozzles are constructed of mild steel with ANSI Class 300 or greater forged steel weld neck flanges. Bottom outlet nozzles are not often used since there is a greater risk of losing the entire tank contents as the result of valve or line failure. However, an ASME-coded tank might be equipped with a bottom outlet (3). A sump and clean-out valve are typically mounted at the bottom. Nozzles are usually double valved as a precautionary measure. The following nozzles are usually specified for mounting on top of the tank (13):

- One 22-inch minimum diameter manhole with cover;
- One manhole for submerged pump;
- One 4- to 6-inch nozzle for vent line;
- Two 2-inch nozzles for inlet line and relief valve; and
- One 1-inch nozzle for level measuring.

Specific release prevention considerations for vessels include: over-pressure protection, temperature control, and corrosion prevention. Relief devices are not usually provided for 55-gallon drums. These drums must be kept from fire exposure, contamination, and mechanical damage. Larger vessels are usually equipped with pressure relief valves as are tank trucks and rail cars. Process vessels are usually protected by pressure relief valves and/or rupture discs. Since sulfur trioxide tends to corrode pressure relief valves, they are frequently separated from the sulfur trioxide by a rupture disc. The pressure relief valve is set to relieve slightly above the design working pressure of the vessel, but well below the maximum allowable working pressure.

Pressure relief valves and rupture discs are designed to prevent explosion by allowing a controlled release of overpressurized contents. These relief systems are usually sized for flashing liquid caused by:

- Fire exposure (NFPA 30);
- Thermal expansion;
- Internal reaction/decomposition; and
- Excess supply rates.

Relief piping must be sized for adequate flow. To avoid direct discharge to the atmosphere, an overflow tank might be provided for overpressured liquid. If there is a possibility that overpressuring may occur due to causes other than liquid thermal expansion, or where there is no overflow receiver, the vessels should be relieved to either a point in the process which can handle the discharge flow, or to a gas absorption system.

The foundations and supports for vessels are important design considerations, especially for large storage vessels and tall equipment such as distillation columns. Supports for storage tanks containing sulfur trioxide are usually concrete saddles. Tubular support legs are usually avoided. The supports must be protected from possible sulfuric acid mist contact since rapid corrosion can result from dilution of the acid with moisture in the air. Fugitive emissions of sulfuric acid mist can lead to significant external corrosion of supports and bolting. These supports should be protected by fugitive emissions control and regular maintenance of structural members. Surface coatings of mastics or polymers may also help retard external corrosion.

Drum storage of sulfur trioxide is common where small to moderate quantities are required. Drum storage temperatures should not exceed 112°F and drums should not be allowed to come in direct contact with hot surfaces. Air pressure is not used to transfer sulfur trioxide from drums; instead drums are

emptied either by gravity flow or by pumping. A drying train is fitted to the vent opening to prevent moist air from being drawn into the drum while emptying.

The reactors used in sulfur trioxide-related processes represent possible sources of major releases since they contain a large portion of the sulfur trioxide used in their respective processes. These reactors must, therefore, be properly constructed of appropriate materials of construction.

The feed to the reactors must be dry since moisture accelerates the corrosion rate of materials used in construction (e.g., carbon steel). Provisions should be made for exclusion of moisture during any process shutdowns, or purging of the reactors at shutdown and before startups.

Since the sulfonation/sulfation reaction is exothermic, a jacketed tubular reactor is commonly used to maintain the desired reaction temperature. Water is the cooling medium. This equipment must be designed to prevent water leakage into the reactor. Provisions must be made for corrective action if such leakage should occur. Common precautions include ensuring that the water pressure is lower than the process fluid pressure, and monitoring the pH of the cooling water. If leakage should then occur, the acid would enter the water system and be detected by the pH monitoring.

A pressure relief system along with a means of gas purging is also incorporated into the reactor designs since hydrogen gas may build up as a result of corrosion. All vents should be routed to a gas scrubber.

Absorption towers and vaporizers present significant release hazards since they contain large amounts of sulfur trioxide in relatively pure form. The conditions under which this equipment operates (especially the vaporizer boiler) are severe and as a result these areas are potential sites for a release.

Piping--

As with sulfur trioxide vessels, sulfur trioxide pipework design must reflect the pressure, temperature, and corrosion concerns associated with use of the chemical. Careful attention must be paid to pipework and associated fittings since failures of this type of equipment are major contributors to accidental releases of chemicals. Regardless of the physical state of the sulfur trioxide, there are some general guidelines for sulfur trioxide piping systems. The first is simplicity of design; the number of joints and connections should be minimized. In addition to being securely supported, pipes should be sloped, with drainage at the low points. Piping should be constructed so as to allow room for thermal expansion of the pipe and should be protected from exposure to fire and high temperatures. Placement of valves should ensure isolation of leaking pipes and equipment. In addition, all piping not enclosed in a heated structure should be heat traced and insulated.

The correct design and use of pipe supports is essential to reduce overstress and vibration which could lead to piping failure. The supports should be designed to handle the load associated with the pipe, operating and testing medium, insulation, and other equipment. Factors which must be considered include thermal expansion and contraction, vibrations caused by pumping and fluid flow, bending moments as a result of overpressure in the pipe, and external loads such as winds or ice accumulation.

At a minimum, piping networks are usually pressure tested to meet the requirements specified by ANSI code B31.3 (17). If a gas is used, it must be dry to prevent corrosion and resulting hydrogen gas formation. If water is used, the piping must be drained and blown dry before use.

As a result of the possible buildup of hydrogen gas from corrosive effects and the relatively low boiling point of sulfur trioxide, rupture due to overpressure is possible especially in liquid-full lines. Protection against this is commonly provided by installing a pressure relief valve or rupture disk (18).

All piping should be situated away from fire and fire hazards since the presence of hydrogen gas could trigger an explosion. If possible, piping carrying sulfur trioxide should not be routed near other processes or piping networks which might present an external threat (e.g., piping carrying highly corrosive materials, high pressure processes). Pipe flanges should be situated so as to minimize potential hazards from drips and small leaks since these could cause rapid external corrosion. In addition, the piping network should be protected from possible impact and other structural damage.

Several types of valves including gate, globe, ball, relief, excess flow, and check configurations are used in sulfur trioxide-containing systems. Valves for sulfur trioxide service should be made of 316 or 347 stainless steel or stainless Alloy 20 (4). Valve stem packing of polytetrafluoroethylene is preferred. Whenever possible valves should be flange-mounted horizontally, and positioned with the valve stem up (13). All valves should be heat traced and insulated. Valves should be purchased with a stainless steel guard to protect the operator against acid leaking through the packing (13).

Pressure relief devices should be installed on all sulfur trioxide containing vessels where the chemical can be blocked in. Such devices are set to relieve at a pressure approximately equal to the design pressure (which is greater than the normal operating pressure) for each specific piece of equipment.

Process Machinery--

Process machinery refers to rotating or reciprocating equipment that may be used in the transfer or processing of sulfur trioxide. This includes pumps which may be used to move liquid sulfur trioxide where gas pressure padding is insufficient or inappropriate. No information is available on compressors that might handle gaseous sulfur trioxide.

Pumps--Many of the concerns and considerations for sulfur trioxide piping and valves also apply to pumps. To assure that a given pump is suitable for a sulfur trioxide service application, the system designer should obtain information from the pump manufacturer certifying that the pump will perform properly in this application.

Pumps should be constructed with materials which are resistant to sulfur trioxide at operating temperatures and pressures. They should be installed dry and oil-free. It is especially important that their design not allow sulfur trioxide or lubricating oil to enter seal chambers where they may contact one other. Sulfur trioxide freezes at a fairly high temperature so temperature considerations are important. The pump's supply tank should have high and low level alarms; the pump should be interlocked to shut off at low supply level or low discharge pressure. External pumps should be situated inside a diked area, and should be accessible in the event of a tank leak.

The type of pump selected depends on pumping requirements and operating conditions. Centrifugal, rotary, positive displacement, and sealless pumps are used to pump sulfur trioxide. The pumps used should be constructed of suitable materials such as 316 on 347 stainless steel, or stainless Alloy 20 which are resistant to sulfur trioxide corrosion (4). Liquid sulfur trioxide can be transferred using submerged pumps, canned pumps, or pumps with dry packing or shaft seals.

Canned motor pumps are centrifugal units in which the motor housing is interconnected with the pump casing. Here, the process liquid actually serves as the bearing lubricant. These pumps must be operated with a flooded suction and freezing must be avoided. An alternative concept is the vertical pump often used on storage tanks. These pumps consist of a submerged impeller housing connected by an extended drive shaft to the motor. The advantages of this arrangement are that the shaft seal is above the maximum liquid level (and is therefore not wetted by the pumped liquid) and the pump is self-priming because the liquid level is above the impeller.

Pumps using stuffing boxes and packing should be provided with double-faced seal chambers designed to prevent sulfur trioxide from contacting any reactive material. These chambers can be purged with an appropriate inert fluid such as dry and oil-free nitrogen, or a suitable seal liquid. The seal gas pressure should exceed the tank pressure by an appropriate margin. A seal fluid back-up system should be considered (19).

Magnetically-coupled pumps are constructed with a rotating magnetic field as the pump-motor coupling device. Diaphragm pumps are positive displacement units in which a reciprocating flexible diaphragm drives the fluid. In both of these pump types, exposure of packing and seals to the pumped liquid is eliminated.

For metering service, diaphragm pumps are commonly used. However, a major consideration in the application of such pumps is that at some point, diaphragm failure will probably occur. Such a failure could lead to a release of the liquid being pumped. These pumps may have a pressure relief valve on the outlet, bypassing to the suction.

Improper operation of pumps as a result of cavitation, running dry, and deadheading can cause damage and failure of pumps. If cavitation is allowed to occur, pitting and eventual serious damage to the impeller can result. Running a pump dry as a result of loss of head in a feed tank, for example, can seriously damage a pump. Finally, pumping against a closed valve can have serious ramifications. A pump bypass or kick-back is useful in avoiding such an occurrence. Failure of a pump, for whatever reason, can eventually lead to a hazardous release.

Centrifugal pumps often have a recycle loop back to the feed container which prevents overheating if the pump is deadheaded. This is an important consideration in sulfur trioxide systems since sulfur trioxide corrosiveness increases with increasing temperature. Deadheading is also a concern with positive displacement pumps. To prevent rupture, positive displacement pumps

commonly have a pressure relief valve which bypasses to the pump suction. Because of the probability of eventual diaphragm failure, the use of diaphragm pumps should be carefully considered in view of this hazard potential.

Pumps are not always necessary; in some circumstances, liquid sulfur trioxide is moved by gravity and/or pressure padding. With sulfur trioxide drums, the liquid may be displaced from the vessel by the force of gravity. With other types of vessels, an inert gas such as dry nitrogen may be used to force liquid from tank. Padding system designs must reflect the operating conditions and limítations (e.g., required flow rate) and therefore must be custom designed for a process.

Miscellaneous Equipment--

Pressure Relief Devices--Information on specific relief valve types for sulfur trioxide service is not readily available. Some characteristics for other hazardous chemical service seem to apply for sulfur trioxide, however. For vessels, an acceptable relief valve is of angle body construction with a closed bonnet and a screwed cap over the adjusting screw. These valves are normally used in combination with a rupture disc or a breaking assembly with a pressure indicator to monitor the pressure of the space between disc and valve. Typical valve construction materials include a cast carbon steel body; nickel plated steel spring; and nickel-copper or nickel-chromium-molybdenum alloy nozzle, disc adjusting ring, nozzle ring, and spindle guide. The inlet flange should be ANSI Class 300 or greater and the outlet flange should be ANSI Class 150 or greater. Valves of this construction which also have fluorinated synthetic rubber "O" ring seat seals need not have a rupture disc or breaking pin. Other types of pressure relief devices are acceptable as long as they are constructed of materials suitable for sulfur trioxide service and meet the general requirements of the ASME boiler and Pressure Vessel Code, Section VIII, Division 1 (17).

Rupture discs are constructed of appropriate sulfur trioxide-resistant materials. Impervious graphite rupture discs fragment upon overpressure, and therefore, should not be used in conjunction with relief valves. Connections can be screwed, flanged or socket-welded for connections smaller than two inches. However, connections two inches or larger should be flanged or butt-welded. The flanges should be constructed of forged carbon steel and be rated in accordance with the associated piping system. Because operating pressures exceeding 70% of a disc's burst pressure may induce premature failure, a considerable margin should be allowed when sizing rupture discs. When it is possible to draw a vacuum on the disc, supports should be provided to prevent damage to the disc (18).

5.3.2 Plant Siting and Layout

The siting and layout of a particular sulfur trioxide facility is a complex issue which requires careful consideration of numerous factors. These include: other processes in the area, the proximity of population centers, prevailing winds, local terrain, and potential natural external effects such as flooding. The rest of this subsection describes general considerations which might apply to siting and layout of sulfur trioxide facilities.

Siting of facilities or individual equipment items should be done in a manner that reduces personnel exposure, both plant and public, in the event of a release. Since there are also other siting considerations, there may be trade-offs between this requirement and others in a process, some directly safety related. Siting should provide ready ingress or egress in the event of an emergency and yet also take advantage of barriers, either man made or natural, which could reduce the hazards of releases. Large distances between large inventories and sensitive receptors (e.g., control room, hazardous process units, population centers) are desirable.

Layout refers to the placement and arrangement of equipment in the process facility. All anhydrous sulfur trioxide, oleum, and sulfuric acid storage and handling equipment should be located away from other potentially hazardous storage and handling facilities. Such equipment is usually located in concrete enclosures or pits surrounded by curbing or walls to prevent acid spills from contaminating surrounding areas and also to serve as a boundary for the restricted acid area. Concrete containment areas are often treated with polymeric sealers to increase the containment efficiency. The drain system for the containment area should be designed to cause storm water to be routed to wastewater treating. The system should be capable of directing spilled sulfur trioxide, oleum, or sulfuric acid to a high capacity neutralization facility.

Various techniques are available for formally assessing a plant layout and should be considered when planning high hazard facilities (18).

General layout considerations include:

- Large inventories of sulfur trioxide should be kept away from potential sources of fire or explosion;

- Vehicular traffic should not be routed too near sulfur trioxide process or storage areas if this can be avoided;

- Where such traffic is necessary, precautions should be taken to reduce the chances for vehicular collisions with equipment, especially pipe racks carrying sulfur trioxide across or next to roadways;

- Sulfur trioxide, oleum or sulfuric acid piping preferably should not be located adjacent to other piping which is under high pressure or temperature, or which carries flammable materials; and

- Storage facilities should be segregated from the main process unless the hazards of pipe transport are felt to outweigh the hazard of the storage tank for site-specific cases.

Because heat increases the corrosiveness of sulfur trioxide and causes thermal expansion of liquid sulfur trioxide, measures should be taken to situate piping, storage vessels, and other sulfur trioxide equipment so they are less exposed to heat sources. Hot process piping, equipment, steam lines, and other sources of direct or radiant heat should be avoided or systems should be designed for heat induced corrosion and pressure increases. Storage areas should also be situated away from control rooms, offices, utilities, other hazardous storage, and laboratory areas by distances similar to those specified for flammable materials (18). Special precautions should be taken to keep sulfur trioxide storage vessels away from potential fire or explosion sources.

In the event of an emergency, there should be multiple means of access to the facility for emergency vehicles and crews. Storage vessel shut-off valves should be readily accessible. Containment around liquid storage tanks can be provided by diking. Dikes reduce evaporation while containing the liquid. It is also possible to equip a diked area to allow drainage to an underground containment sump. This sump should vented to a scrubber system for safe discharge. A hot room can also serve as a full containment system if it is designed to vent to a scrubber. This type of secondary containment could be considered for large-volume liquid sulfur trioxide storage tanks.

5.3.3 Transfer and Transport Facilities

Transfer and transport facilities where both road and rail tankers are loaded or unloaded are potential accident areas because of vehicle movement and the intermittent nature of the operations. Therefore, special attention should be given to the design of these facilities.

As mentioned in the previous section, tank car and tank truck facilities should be located away from sources of heat, fire, and explosion. Equipment in these areas should also be protected from impact by vehicles and other moving equipment. Tank vehicles should be securely moored during transfer operations; an interlocked barrier system is commonly used. Sufficient space should be available to avoid congestion of vehicles or personnel during loading and unloading operations. Vehicles, especially trucks, should be able to move into and out of the area without reversing. High curbs around transfer areas and barriers around equipment should be provided to protect equipment from vehicle collisions.

When possible, the transfer of sulfur trioxide should be made using fixed rigid piping. In situations which require flexible hoses or tubes, precautions must be taken to ensure sound connections. Avoiding cross-contamination of chemical materials is also a key concern.

5.4 PROTECTION TECHNOLOGIES

This subsection describes two types of protection technologies for containment and neutralization. These are:

- Enclosures; and
- Scrubbers.

A presentation of more detailed information on these systems is presented in a companion manual on control technologies of the prevention reference manual series.

5.4.1 Enclosures

Enclosures refer to containment structures which capture any sulfur trioxide spilled or vented from storage or process equipment, thereby preventing immediate discharge of the chemical to the environment. The enclosures

contain the spilled liquid or gas until it can be transferred to some other type of containment, discharged at a controlled rate which would not be injurious to people or the environment, or transferred at a controlled rate to scrubbers for neutralization.

The use of specially designed enclosures for sulfur trioxide storage appears to be fairly common. It is not known whether sulfur trioxide process equipment is typically enclosed or not. If the process is enclosed, the enclosure is a hot room which is primarily designed to maintain the liquid or vaporized sulfur trioxide temperature at 95 to 105°F (20). Locating toxic operations in the open air has been mentioned favorably in the literature, along with the opposing idea that sometimes enclosures may be appropriate (18). The desirability of enclosure depends partly on the frequency with which personnel must be involved with the equipment. A common design rationale for not having an enclosure where toxic materials are used is to prevent the accumulation of toxic concentrations of a chemical within a work area. However, if the issue is protecting the community from accidental releases, then total enclosure may be appropriate.

Care must be taken when an enclosure is built around pressurized equipment. It would not be practical to design an enclosure to withstand the pressures associated with the sudden failure of a pressurized vessel. An enclosure would probably fail as a result of the pressure created from such a release and could create an additional hazard. In these situations, it may be determined that an enclosure is not appropriate. If an enclosure is built around pressurized equipment then it should be equipped with some type of explosion protection, such as rupture plates that are designed to fail before the entire structure fails.

The types of structures that appear to be suitable for sulfur trioxide storage and process equipment are buildings or bunkers constructed of concrete. If silicate concrete is used, these structures would be resistant to attack by sulfur trioxide or sulfuric acid mist (15). The building should

have a ventilation system designed to draw in air when the building is vented to a scrubber. The bottom section of the building should be liquid tight to retain any liquid sulfur trioxide that might be spilled. There should be a minimum of two exits which have doors elevated and accessible by steps inside and outside. The room should also include a valved draw-off line from below floor level to permit removal of the flooded liquid sulfur trioxide to a backup storage system. Enclosures should be equipped with continuous monitoring equipment and alarms. Alarms should sound whenever detected concentrations are approaching lethal levels.

5.4.2 Scrubbers

Scrubbers are a traditional method for absorbing toxic gases from process streams. These devices can be used for the control of sulfur trioxide releases from vents and pressure relief discharges, from process equipment, or from secondary containment enclosures.

Sulfur trioxide discharges could be contacted with sulfuric acid (93% or greater) in any of several types of scrubbing devices. Makeup water would be added to maintain the desired acid strength. Types of scrubbers that might be appropriate include spray towers, packed bed scrubbers, and venturis. Other types of special designs might be suitable, but complex internals subject to corrosion do not seem to be advisable.

Whatever type of scrubber is selected, a complete system would include the scrubber itself, a liquid feed system, makeup equipment, reservoir, demister and a blower for some systems. If such a system is used as protection against emergency releases, consideration must be given to how it would be activated in time to respond to an emergency load. One approach used in some process facilities is to maintain a continuous circulation of scrubbing acid through the system. For many facilities this would not be practical, and the scrubber system might be tied into a trip system to turn it on when it is

needed. However, with this system a quantity of sulfur trioxide would be released prior to actuation of the scrubber (i.e., starting up a blower and turning on the flow of liquid).

The scrubber system must be designed so as not to present excessive resistance to the flow of an emergency discharge. The pressure drop should be only a small fraction of the total pressure drop through the emergency discharge system. In general, at the liquid-to-gas ratios required for effective scrubbing, spray towers have the lowest, and venturis the highest pressure drops. While packed beds may have intermediate pressure drops at proper liquid-to-gas ratios, excessive ratios or plugging can increase the pressure drop substantially. However, packed beds have higher removal efficiencies than spray towers or venturis.

In addition, the scrubber system must be designed to handle the "shock wave" generated during the initial stages of the release. This is particularly important for packed bed scrubbers since there is a maximum pressure with which the gas can enter the packed section without damaging the scrubber internals.

5.5 MITIGATION TECHNOLOGIES

If, in spite of all precautions, a large release of sulfur trioxide were to occur, the first priority would be to rescue workers in the immediate vicinity of the accident and evacuate persons from downwind areas. The source of the release should be determined, and the leak should be stopped if possible. The next primary concern becomes reducing the consequences of the released chemical to the plant and the surrounding community. Reducing the consequences of an accidental release of a hazardous chemical is referred to as mitigation. Mitigation technologies include such measures as physical barriers, water sprays and fogs, and foams where applicable. The purpose of a mitigation technique is to divert, limit, or disperse the chemical that has been spilled or released to the atmosphere in order to reduce the atmospheric

concentration and the area affected by the chemical. The mitigation technology chosen for a particular chemical depends on the specific properties of the chemical including its flammability, toxicity, reactivity, and those properties which determine its dispersion characteristics in the atmosphere.

If a release occurs from a liquid sulfur trioxide storage tank, the exposed liquid will immediately combine with moisture in the air to form sulfuric acid mist ("smoke"). The tremendous volumes of "smoke" can obscure vision and make location of the source of the release more difficult. Property damage and personal injury may also result from contact with sulfuric acid mist. It is therefore desirable to minimize the liquid sulfur trioxide surface area exposure which in turn will minimize the rate of mist formation. Mitigation technologies which are used to reduce the surface area exposure include secondary containment systems such as dikes, sumps, and enclosures.

A post-release mitigation effort requires that the source of the release be accessible to trained plant personnel. Therefore, the availability of adequate personnel protection is essential. Personnel protection will typically include such items as portable breathing air and chemically resistant protective clothing.

5.5.1 Secondary Containment Systems

Specific types of secondary containment systems include excavated basins, natural basins, dikes (earth, steel, or concrete) and high impounding walls. The type of containment system best suited for a particular storage tank or process unit will depend on the risk associated with an accidental release from that location. The inventory of sulfur trioxide and its proximity to other portions of the plant and to the community should be considered when selecting a secondary containment system. The secondary containment system should have the ability to contain spills with a minimum of damage to the facility and its surroundings and with minimum potential for escalation of the event.

Secondary containment systems for sulfur trioxide storage facilities commonly consist of one of the following:

- An adequate drainage system underlying the storage vessels which terminates in an impounding basin having a capacity as large as the largest tank served; and

- A diked area, with a capacity as large as the largest tank served.

These measures are designed to prevent the accidental discharge of liquid sulfur trioxide from spreading to uncontrolled areas.

The most common type of containment system is a low wall dike surrounding one or more storage tanks. Generally, no more than three tanks are enclosed within one diked area to reduce risk. Dike heights usually range from three to twelve feet depending on the area available to achieve the required volumetric capacity. The dike walls should be liquid tight and able to withstand the hydrostatic pressure and temperature of a spill. Low wall dikes may be constructed of steel, concrete or earth. If earthen dikes are used, care must be taken to ensure that the sulfur trioxide cannot leak through the dike. Piping should be routed over dike walls, and penetrations through the walls should be avoided if possible. Vapor fences may be situated on top of the dikes to provide additional vapor containment. If there is more than one tank in the diked area, the tanks should be situated on berms above the maximum liquid level attainable in the impoundment.

A low wall dike can effectively contain the liquid portion of an accidental release and keep the liquid from entering uncontrolled areas. By preventing the liquid from spreading, the low wall dike can reduce the surface area of the spill. Reducing the surface area will reduce the rate of evaporation. The low wall dike will partially protect the spill from wind; this can reduce the rate of evaporation. A dike with a vapor fence will provide extra protection from wind and will be even more effective at reducing the rate of evaporation.

A dike also creates the potential for sulfur trioxide and trapped water to mix within the enclosed area. This may accelerate the rate of evaporation and form large quantities of highly corrosive sulfuric acid mist. If materials that would react violently with sulfur trioxide are stored within the same diked area then the dike will increase the potential for mixing the materials in the event of a simultaneous leak. A dike also limits access to the tank during a spill.

An impounding basin is well suited to storage systems where more than one tank is served and a relatively large site is available for such a basin. The spilled sulfur trioxide is directed to the basin by dikes and channels under the storage tanks which are designed to minimize exposure of the other tanks and surrounding facilities to the spilled liquid. Because of the high vapor pressure of sulfur trioxide, the trenches that lead to the basin should be covered to reduce the rate of evaporation. Additionally, the basin should be located near the tank area to minimize the amount of sulfur trioxide that evaporates as it travels to the basin.

This type of system has several advantages. The spilled liquid is removed from the immediate tank area. This allows access to the tank during the spill and reduces the probability that the spilled liquid will damage the tank, piping, electrical equipment, pumps or other equipment. In addition, the covered impoundment will reduce the rate of evaporation from the spill by isolating the spill from wind or heating from sunlight.

A limitation of a remote impounding basin is that there is still the potential for water or other incompatible materials to be trapped in the impoundment and mix with the incoming sulfur trioxide. Remote impounding basins do not reduce the impact of a gaseous sulfur trioxide release.

High wall impoundments may be a good secondary containment choice for selected systems. Circumstances which may warrant their use include limited storage site area, the need to minimize vapor generation rates, and/or the

tank must be protected from external hazards. Maximum vapor generation rates will generally be lower for high wall impoundments than for low wall dikes or for remote impoundments because of the reduced surface area. These rates can be further reduced with the use of insulation on the wall and floor in the annular space. High impounding walls may be constructed of low temperature steel, reinforced concrete, or prestressed concrete. A weather shield may be provided between the tank and wall with the annular space remaining open to the atmosphere. The available area surrounding the storage tank will dictate the minimum height of the wall. For high wall impoundments, the walls may be designed with a volumetric capacity greater than that of the tank to provide vapor containment. Increasing the height of the wall also raises the elevation of any released vapor.

One disadvantage of these dikes is that the high walls around a tank may hinder routine external observation. Furthermore, the closer the wall is to the tank, the more difficult it becomes to access the tank for inspection and maintenance. As with low wall dikes, piping should be routed over the wall if possible. The closeness of the wall to the tank may necessitate placement of the pump outside the wall, in which case the outlet (suction) line will have to pass through the wall. In such a situation, a low dike encompassing the pipe penetration and pump may be provided, or a low dike may be placed around the entire wall.

One further type of secondary containment system is one which is structurally integrated with the primary system and forms a vapor-tight enclosure around the primary container. Many types of arrangements are possible. A double-walled tank is an example of such an enclosure. These systems may be considered where protection of the primary container and containment of vapor (for events not involving foundation or wall penetration failure) are of greatest concern. Drawbacks of an integrated system are the greater complexity of the structure, the difficulty of access to certain components, and the fact that complete vapor containment cannot be guaranteed for all potential events.

Provision should be made for drainage of rainwater from diked areas. This will involve the use of sumps and separate drainage pumps, since direct drainage to stormwater sewers would presumably allow any spilled sulfur trioxide to follow the same route. Alternatively, a sloped rain hood may be used over the diked area which could also serve to direct the rising vapors to a single release point (20). The ground within the enclosure should be graded to cause the spilled liquid to accumulate at one side or in one corner. This will help to minimize the area of ground to which the liquid is exposed and from which it may gain heat. In areas where it is critical to minimize vapor generation, surface insulation may be used in the diked area to further reduce heat transfer from the environment to the spilled liquid. The floor of an impoundment should be sealed with a clay blanket to prevent the sulfur trioxide from seeping into the ground; percolation into the ground causes the ground to cool more quickly, increasing the vapor generation rate. Absorption of the sulfur trioxide into water in the soil would also release additional heat.

5.5.2 Flotation Devices and Foams

Other possible means of reducing the surface area of spilled hazardous chemicals include placing impermeable devices on the surface, dilution with water, and applying water-based foam. However, where sulfur trioxide releases are concerned, none of these are completely satisfactory.

Placing a surface seal over a spilled chemical is a direct approach for containing toxic vapors with nearly 100 percent efficiency. One such material has been developed and tested to rapidly stop the generation of sulfuric acid mist ("smoke") from a confined pool of liquid sulfur trioxide (21). The surface seal is made of an inert halocarbon oil slurried with hollow glass bubbles to make the oil float on the surface of the liquid sulfur trioxide. The slurry can be mixed in advance for storage, but it must be remixed at weekly intervals to prevent stratification and setting. The surface seal is effective at capping a confined pool of liquid sulfur trioxide, such as contained in a reservoir or sump.

The use of foams in vapor hazard control has been demonstrated for a broad range of volatile chemicals. However, since foams still contain water they will react with sulfur trioxide to form sulfuric acid mist. Results of a laboratory test program to develop a method for the containment and blanketing of liquid sulfur trioxide spills showed that a mechanical foam is the fastest method available to stop the "smoke" from a large or uncontrolled spill in an unconfined area (3). A mechanical foam is a fluid aggregate of small bubbles containing water dispersed in very thin films that make up the bubbles. Mechanical foam should not be used in a confined area since the foam can react violently with liquid sulfur trioxide to form hazardous sulfuric acid mist.

Finally, the dilution of a sulfur trioxide spill with water will result in huge volumes of sulfuric acid mist or "smoke". Extreme caution should be exercised using water of any kind, since violent spattering can occur. To minimize spattering, a water fog or fine spray should be used (4). The reaction of liquid sulfur trioxide with a water fog or spray is less violent than the reaction with a full water stream. Water would be appropriate only when the spill is too large to be controlled using absorbent material or a surface seal.

One alternative for sulfur trioxide spills is to spread a non-reactive absorbent material such as expanded clay or diatomaceous earth. Once absorbed, the sulfur trioxide residue can be removed from the area for dilution with water, or neutralization with solutions of caustic materials.

5.6 OPERATION AND MAINTENANCE PRACTICES

Quality hardware, contained mechanical equipment, and protective devices all increase plant safety; however, they must be supported by the safety policies of management and by constraints on their operation and maintenance. This section describes how management policy and training, operation, and maintenance procedures relate to the prevention of accidental sulfur trioxide releases. Within the sulfur trioxide industry, these procedures and practices

vary widely because of differences in the size and nature of the processes and because any determination of their adequacy is inherently subjective. For this reason, the following subsections focus primarily on fundamental principles and do not attempt to define specific policies and procedures.

5.6.1 Management Policy

Management is a key factor in the control of industrial hazards and the prevention of accidental releases. Management establishes the broad policies and procedures which influence the implementation and execution of specific hazard control measures. It is important that these management policies and procedures be designed to match the level of risk in the facilities where they will be used. Most organizations have a formal safety policy. Many make policy statements to the effect that safety must rank equally with other company functions such as production and sales. The effectiveness of any safety program, however, is determined by a company's commitment to it, as demonstrated throughout the management structure. Specific goals must be derived from the safety policy and supported by all levels of management. Safety and loss prevention should be an explicit management objective. Ideally, management should establish the specific safety performance measures, provide incentives for attaining safety goals, and commit company resources to safety and hazard control. The advantages of an explicit policy are that it sets the standard by which existing programs can be judged, and it provides evidence that safety is viewed as a significant factor in company operations.

In the context of accident prevention, management is responsible for (17,22):

- Ensuring worker competency;
- Developing and enforcing standard operating procedures;
- Adequate documentation of policy and procedures;
- Communicating and promoting feedback regarding safety issues;
- Identification, assessment, and control of hazards; and
- Regular plant audits and provisions for independent checks.

Additional discussion on the responsibilities of management can be found in a manual on control technologies, part of this manual series.

5.6.2 Operator Training

The performance of operating personnel is also a key factor in the prevention of accidental sulfur trioxide releases. Many case studies documenting industrial incidents note the contribution of human error to accidental releases (17). Release incidents may be caused by using improper routine operating procedures, by insufficient knowledge of process variables and equipment, by lack of knowledge about emergency or upset procedures, by failure to recognize critical situations, and in some cases by direct physical mistake (e.g., turning the wrong valve). A comprehensive operator training program can decrease the potential for accidents resulting from such causes.

Operator training can include a wide range of activities and a broad spectrum of information. Training, however, is distinguished from education in that it is specific to particular tasks. While general education is important and beneficial, it is not a substitute for specific training. The content of a specific training program depends on the type of industry, the nature of the processes used, the operational skills required, the characteristics of the plant management system, and tradition.

Some general characteristics of quality industrial training programs include:

- Establishment of good working relations between management and personnel;
- Definition of trainer responsibilities and training program goals;
- Use of documentation, classroom instruction, and field training (in some cases supplemented with simulator training);

- Inclusion of procedures for normal startup and shutdown, routine operations, and upsets, emergencies, and accidental releases; and

- Frequent supplemental training and the use of up-to-date training materials.

In many instances training is carried out jointly by plant managers and a training staff selected by management. In others, management is solely responsible for maintaining training programs. In either case, responsibilities should be explicitly designated to ensure that the quality and quantity of training provided is adequate. Training requirements and practices can be expected to differ between small and large companies, partly because of resource needs and availability, and partly because of differences in employee turnover.

A list of the aspects typically involved in the training of process operators for routine process operations is presented in Table 5-3.

Emergency training includes topics such as:

- Recognition of alarm signals;
- Performance of specific functions (e.g., shutdown switches);
- Use of specific equipment;
- Actions to be taken on instruction to evacuate;
- Fire fighting; and
- Rehearsal of emergency situations.

Aspects specifically addressed in safety training include (17, 22):

- Hazard recognition and communication;

- Actions to be taken in particular situations;

TABLE 5-3. ASPECTS OF TRAINING PROGRAMS FOR ROUTINE PROCESS OPERATIONS

Process goals, economics, constraints, and priorities
Process flow diagrams
Unit operations
Process reactions, thermal effects
Control systems
Process materials quality, yields
Process effluents and wastes
Plant equipment and instrumentation
Equipment identification
Equipment manipulation
Operating procedures
Equipment maintenance and cleaning
Use of tools
Permit systems
Equipment failure, services failure
Fault administration
Alarm monitoring
Fault diagnosis
Malfunction detection
Communications, recordkeeping, reporting

Source: Reference 17.

- Available safety equipment and locations;

- Use and familiarity with documentation such as;
  - plant design and operating manuals,
  - company safety rules and procedures,
  - procedures relevant to fire, explosion, accident, and health hazards,
  - chemical property and handling information; and

- First aid and CPR.

Although emergency and safety programs typically focus on incidents such as fires, explosions, and personnel safety, it is important that prevention of chemical releases and release responses be addressed as part of these programs.

Much of the type of training discussed above is also important for management personnel. Safety training gives management the perspective necessary to formulate good policies and procedures, and to make changes that will improve the quality of plant safety programs. Lees suggests that training programs applied to managers include or define (17):

- Overview of technical aspects of safety and loss prevention approach;

- Company systems and procedures;

- Division of labor between safety personnel and managers with respect to training; and

- Familiarity with documented materials used by workers.

5.6.3 Maintenance and Modification Practices

Plant maintenance is necessary to ensure the structural integrity of chemical processing equipment; modifications are often necessary to allow more effective production. However, since these activities are also a primary source of accidental release incidents, proper maintenance and modification practices are an important part of accidental release prevention. Use of a formal system of controls is perhaps the most effective way of ensuring that maintenance and modification are conducted safely. In many cases, control systems have had a marked effect on the level of failures experienced (17).

Permit systems and up-to-date maintenance procedures minimize the potential for accidents during maintenance operations. Permit-to-work systems control maintenance activities by specifying the work to be done, defining individual responsibilities, eliminating or protecting against hazards, and ensuring that appropriate inspection and testing procedures are followed.

Maintenance permits originate with the operating staff. Permits may be issued in one or two stages. In one-stage systems, the operations supervisor issues permits to the maintenance supervisor, who is then responsible for his staff. Two-stage systems involves a second permit issued by the maintenance supervisor to his workforce (17).

Another form of maintenance control is the maintenance information system. Ideally, these systems should log the entire maintenance history of equipment, including preventative maintenance, inspection and testing, routine servicing, and breakdown or failure maintenance. This type of system is also used to track incidents caused by factors such as human error, leaks, and fires, including identification and quantification of failures responsible for hazardous conditions, failures responsible for downtime, and failures responsible for direct repair costs.

Accidental releases are frequently the result of some aspect of plant modification. Accidents result when equipment integrity and operation are not properly assessed following modification, or when modifications are made without updating corresponding operation and maintenance instructions. In these situations, it is important that careful assessment of the modification results has a priority equal to that of getting the plant on-line.

For effective modification control, there must be established procedures for authorization, work activities, inspection and assessment, complete documentation of changes, including the updating of manuals, and additional training to familiarize operators with new equipment and procedures (17, 22).

Formal procedures and checks on maintenance and modification practices must be established to ensure that such practices enhance rather than adversely affect plant safety. As with other plant practices, procedure development and complete documentation are necessary. However, training, attitude, and the degree to which the procedures are followed also significantly influence plant safety and release prevention.

The use and availability of clearly defined procedures collected in maintenance and operating manuals is crucial for the prevention of accidental releases. Well-written instructions should give enough information about the process that the worker with hands-on responsibility for operating or maintaining the process can do so safely, effectively, and economically. These instructions not only document the path to the desired results, but also are the basis for most industrial training programs (23, 24). In the chemical industry, operating and maintenance manuals vary in content and detail. To some extent, this variation is a function of process type and complexity; however, in many cases it is a function of management policy. Because of their importance to the safe operation of a chemical process, these manuals must be as clear, straightforward, and complete as possible. In addition, standard procedures should be developed and documented before plant startup, and appropriate revisions should be made throughout plant operations.

Operation and maintenance may be combined or documented separately. Procedures should include startup, shutdown, hazard identification, upset conditions, emergency situations, inspection and testing, and modifications (17). Several authors think industrial plant operating manuals should include (17, 22, 23, 24):

- Process descriptions;
- A comprehensive safety and occupational health section;
- Information regarding environmental controls;
- Detailed operating instructions, including startup and shutdown procedures;
- Upset and emergency procedures;
- Sampling instructions;
- Operating documents (e.g., logs, standard calculations);
- Procedures related to hazard identification;
- Information regarding safety equipment;
- Descriptions of job responsibilities; and
- Reference materials.

Plant maintenance manuals typically contain procedures not only for routine maintenance, but also for inspection and testing, preventive maintenance, and plant or process modifications. These procedures include specific items such as codes and supporting documentation for maintenance and modifica-

tions (e.g., permits-to-work, clearance certificates), equipment identification and location guides, inspection and lubrication schedules, information on lubricants, gaskets, valve packings and seals, maintenance stock requirements, standard repair times, equipment turnaround schedules, and specific inspection codes (e.g., for vessels and pressure systems) (17). Full documentation of the maintenance required for protective devices is a particularly important aspect of formal maintenance systems.

The preparation of operating and maintenance manuals, their availability, and the familiarity of workers with their contents are all important to safe plant operations. The objective, however, is to maintain this safe practice throughout the life of the plant. Therefore, as processes and conditions are modified, documented procedures must also be modified.

5.7 CONTROL EFFECTIVENESS

It is difficult to quantify the control effectiveness of preventive and protective measures to reduce the probability and magnitude of accidental releases. Preventive measures, which may involve numerous combinations of process design, equipment design, and operational measures, are especially difficult to quantify because they reduce a probability of a chemical release rather than a physical quantity of chemical release. Protective measures are more analogous to traditional pollution control technologies. Thus, they may be easier to quantify in terms of their efficiency in reducing a quantity of chemical that could be released.

Preventive measures reduce the probability of an accidental release by increasing the reliability of both process systems operations and the equipment. Control effectiveness can thus be expressed for both the qualitative improvements and the quantitative improvements through probabilities. Table 5-4 summarizes what appear to be some of the major design, equipment, and operational measures applicable to the primary hazards identified for the sulfur trioxide applications in the United States. The items listed in Table

TABLE 5-4. EXAMPLES OF MAJOR PREVENTION AND PROTECTION MEASURES FOR SULFUR TRIOXIDE RELEASES

Hazard Type	Prevention/Protection
OPERATIONAL	
Human error	Increased training and supervision; use of checklists; use of automatic systems
Vehicular collisions	Location; physical barriers; warning signs; training
Overfilling	Redundant independent level sensing, alarms, and interlocks; training of operators
PROCESS	
Water contamination in organic feeds to sulfonation/sulfation	Continuous moisture monitoring; Backflow prevention
Sulfur trioxide flow control	Redundant flow control loops; Minimal overdesign of feed systems
Temperature sensing and cooling medium flow control	Redundant temperature sensors; Interlock flow switch to shut off SO_3 feed on loss of cooling, with relief venting to emergency scrubber system
Temperature sensing and heating medium flow control	Redundant temperature sensors; Interlock flow switch to shut off SO_3 feed on loss of heating, with relief venting to emergency scrubber system
Reactor and vaporizer temperatures	Redundant temperature sensing and alarms
Overpressure	Redundant pressure relief; adequate size; discharge not restricted
Atmosphere releases from relief discharges	Emergency vent scrubber system

(Continued)

TABLE 5-4. (Continued)

Hazard Type	Prevention/Protection
EQUIPMENT	
Vessel failure	Adequate pressure relief; inspection and maintenance; corrosion monitoring; siting away from fire and mechanical damage; higher pressure rating in the event of solid SO_3 formation and required remelting
Corrosion	Increased monitoring with more frequent inspections; use of pH sensing on cooling water and steam condensate loops; use of corrosion coupons[a]; visual inspections; non-destructive testing
Storage tank or line rupture	Enclosure vented to emergency scrubber system; diking; foams; dilution; neutralization; water sprays

[a] A piece of metal of known composition which is used to monitor corrosion rates by allowing it to reside in the corrosive environment and measuring the amount of corrosion as a function of time.

5-4 are for illustration only and do not necessarily represent satisfactory control options for all cases. These control options appear to reduce the risk associated with an accidental release when viewed from a broad perspective. However, there are undoubtedly specific cases where these control options will not be appropriate. Each case must be evaluated individually. A presentation of more information about reliability in terms of probabilities is discussed in the manual on control technologies, part of this prevention reference manual series.

5.8 ILLUSTRATIVE COST ESTIMATES FOR CONTROLS

This section presents cost estimates for different levels of control and for specific release prevention and protection measures for sulfur trioxide storage and process facilities that might be found in the United States.

5.8.1 Prevention and Protection Measures

Preventive measures reduce the probability of an accidental release from a process or storage facility by increasing the reliability of both process systems operations and equipment. Along with an increase in the reliability of a system is an increase in the capital and annual costs associated with incorporating prevention and protection measures into a system. Table 5-5 presents costs for some of the major design, equipment, and operational measures applicable to the primary hazards identified in Table 5-4 for the sulfur trioxide applications in the United States.

5.8.2 Levels of Control

Prevention of accidental releases relies on a combination of technological, administrative, and operational practices as they apply to the design, construction, and operation of facilities where hazardous chemicals are used and stored. Costs are inherent in determining the degree to which these practices are carried out. At a minimum, equipment and procedures should be

TABLE 5-5. ESTIMATED TYPICAL COSTS OF MAJOR PREVENTION AND PROTECTION MEASURES FOR SULFUR TRIOXIDE RELEASE[a]

Prevention/Protection Measure	Capital Cost (1986 $)	Annual Cost (1986 $/yr)
Continuous moisture monitoring	7,500-10,000	900-1,300
Flow control loop	4,000-6,000	500-750
Temperature sensor	250-400	30-50
Pressure relief		
- relief valve	1,000-2,000	120-250
- rupture disk	1,000-1,200	120-150
Interlock system for flow shut-off	1,500-2,000	175-250
pH monitoring of cooling water	7,500-10,000	900-1,300
Alarm system	250-500	30-75
Level sensor		
- liquid level gauge	1,500-2,000	175-250
- load cell	10,000-15,000	1,300-1,900
Diking (based on a 10,000 gal. tank)		
- 3 ft. high	1,200-1,500	150-175
- top of tank height, 10 ft.	7,000-7,500	850-900
Increased corrosion inspection[b]		200-400

[a]Based on a 10,000 gallon fixed sulfur trioxide storage tank system and a 20 million pounds per year capacity sulfonate detergent process.

[b]Based on 10-20 hr. @ $20/hr.

in accordance with applicable codes, standards, and regulations. However, additional measures can be taken to provide extra protection against an accidental release.

The levels-of-control concept provides a means of assigning costs to increased levels of prevention and protection. The minimum level is referred to as the "Baseline" system. This system consists of the elements required for normal safe operation and basic prevention of an accidental release of hazardous material.

The second level of control is "Level 1". "Level 1" includes the "Baseline" system with added modifications such as improved materials of construction, additional controls, and generally more extensive release prevention measures. The costs associated with this level are higher than the baseline system costs.

The third level of control is "Level 2." This system incorporates both the "Baseline" and "Level 1" systems with additional modifications designed specifically for the prevention of an accidental release such as alarm and interlock systems. The extra accidental release prevention measures incorporated into "Level 2" are reflected in its cost, which is much higher than that of the baseline system.

When comparing the costs of the various levels of control, it is important to realize that higher costs do not necessarily imply improved safety. The measures applied must be applied correctly. Inappropriate modifications or add-ons may not make a system safer. Each added control option increases the complexity of a system. In some cases the hazards associated with the increased complexity may outweigh the benefits derived from the particular control option. Proper design and construction along with proper operational practices are needed to assure safe operation.

These estimates are for illustrative purposes only. It is doubtful that any specific installation would find all of the control options listed in these tables appropriate for their purposes. An actual system is likely to incorporate some items from each of the levels of control and also some control options not listed here. The purpose of these estimates is to illustrate the relationship between cost and control, and is not to provide an equipment check list.

Two sets of cost estimates were prepared; one for a 10,000 gallon capacity fixed liquid sulfur trioxide storage tank system and the other for a liquid sulfur trioxide sulfonation reactor system for a 20 million pounds per year capacity sulfonate detergent process. These systems are representative of storage and process facilities that might be found in the United States.

5.8.3 Cost Summaries

Table 5-6 presents a summary of the total capital and annual costs for each of the levels of control for the liquid sulfur trioxide storage system and the added level of control for the liquid sulfur trioxide sulfonation reactor system. The costs presented correspond to the systems described in Table 5-7 and Table 5-8. Costs associated with each of the levels include the cost of the basic system plus any added controls. Specific costs and cost information for each level of control for both the storage and process facilities are presented in Tables 5-9 through 5-13.

5.8.4 Equipment Specifications and Detailed Costs

Equipment specifications and details of the capital cost estimates for the liquid sulfur trioxide storage and the liquid sulfur trioxide sulfonation reactor systems are presented in Tables 5-14 through 5-20.

TABLE 5-6. SUMMARY COST ESTIMATES FOR POTENTIAL LEVELS OF CONTROLS FOR SULFUR TRIOXIDE STORAGE TANK AND SULFONATION SYSTEM

System	Level of Control	Total Capital Cost (1986 $)	Total Annual (1986 $)
Fixed SO_3 storage tank with 10,000 gallon capacity	Baseline	116,000	14,000
	Level No. 1	210,000	25,000
	Level No.2	679,000	80,000
SO_3 sulfonation reactor system with a 20 million pounds per year capacity	Baseline	2,174,000	261,000
	Level No. 1[a]	2,404,000	289,000

[a]Only one level of control in addition to the baseline was costed since the baseline system inherently includes many of the controls discussed in this manual. Level 1 simply provides redundant control measures.

TABLE 5-7. EXAMPLE OF LEVELS OF CONTROL FOR SULFUR TRIOXIDE STORAGE TANK[a]

Process: 10,000 gal fixed liquid sulfur trioxide storage tank

Controls	Baseline	Level No. 1	Level No. 2
Flow:	Single check-valve on tank-process feed line.	Add second check valve.	Add a reduced-pressure device with internal air gap and relief vent to contaminant tank or scrubber.
Temperature:	Local temperature indicator. Temp sensor with controller regulating immersion heater and heat tracing.	Add remote temperature indicator. Temp sensor w/controller regulating immersion heater and heat tracing.	Add temperature alarm. Temperature sensor with controller regulating hot-room heater and immersion heater.
Pressure:	Single pressure relief valve, vent to atmosphere.	Add second relief valve w/3-way valve. Vent to limited scrubber. Local pressure indicator.	Add rupture discs under relief valves. Provide local pressure indication on space between disc and valve. Vent to scrubber.
Quantity:	Local level indicator.	Independent remote level indicator.	Add level alarm. Add high-low level interlock shutoff for inlet and outlet lines.
Location:	Away from traffic, flammables, and other hazardous processes.	Same	Same
Materials of Construction:	Carbon steel.	Carbon steel with increased corrosion allowances. 1/8 inch.	304SS.

(Continued)

TABLE 5-7. (Continued)

Controls	Baseline	Level No. 1	Level No. 2
Vessel:	Tank pressure specification 50 psig. Heat traced and insulated.	Tank pressure specification 100 psig. Heat traced and insulated.	Tank pressure specification 100 psig.
Piping:	Sch. 80 carbon steel. Heat traced and insulated.	Sch. 80 304 SS. Heat traced and insulated.	Sch. 80 Monel
Process Machinery:	Bottom discharge from tank to centrifugal pump, Alloy 20 construction.	Submerged centrifugal pump, Alloy 20 construction.	Magnetically-coupled centrifugal pump, Alloy 20 construction.
Enclosures:	None	None.	Concrete building.
Diking:	None	3 ft. high.	3 ft. high.
Scrubbers:	None	Small acid scrubber.	Large acid scrubber w/hotroom vent scrubber.
Mitigation:	None	Foam generator.	Fluorocarbon surface seal.

[a]The examples in this table are appropriate for many, but not all applications. This is only an exemplary system. Design must be suited to fit the service.

TABLE 5-8. EXAMPLE OF LEVELS OF CONTROL FOR SULFUR TRIOXIDE SULFONATION REACTOR

Process: Sulfur Trioxide Sulfonation
Typical Operating Conditions: - Temperature 95-130'F
- Pressure: 30-40 psig

Controls	Baseline	Level No. 1
Temperature:	Provide local temperature indicators on all process streams and on the utility fluid streams entering and leaving the heat exchangers. Remote temperature indicators and controllers.	Add redundant temperature sensors and alarms.
Pressure:	Provide local pressure indicators on all fluid streams and at pump discharges. Single relief valve on reactor. Vent to scrubber.	Add remote pressure indicators. Add second relief valve.
Flow:	Provide local flow indicators on all process streams. Provide local flow control on reactor recycle line and SO_3 vaporizer.	Add redundant flow control loops.
Corrosion:	Visual inspection and periodic pH monitoring of cooling water.	Add continuous pH sensing of cooling water. Add corrosion coupons.
Material of Construction:	316 Stainless Steel.	316 Stainless Steel.
Protective Barrier:	Curbing around reactor/ settler.	3 ft. high retaining wall.
Enclosures:	None	Steel building.
Scrubber:	Caustic venturi scrubber.	ESP with SO_3 scrubber.

TABLE 5-9. ESTIMATE OF TYPICAL CAPITAL AND ANNUAL COSTS ASSOCIATED WITH BASELINE SULFUR TRIOXIDE STORAGE SYSTEM

	Capital Cost (1986 $)	Annual Cost (1986 $/yr)
VESSELS:		
Storage Tank	63,000	7,300
Immersion Heater	4,800	570
Insulation	18,000	2,100
PIPING AND VALVES:		
Pipework	9,900	1,100
Check Valve	530	60
Globe Valves (7)	2,800	330
Relief Valve	1,600	190
Heat Tracing	710	80
Insulation	1,900	220
PROCESS MACHINERY:		
Centrifugal Pump	4,000	460
INSTRUMENTATION:		
Liquid Level Gauge	1,500	170
Local Temperature Indicator	1,900	220
Temperature Control		
- Controller	1,900	220
- Sensor	190	25
- Control Valve	2,800	330
PROCEDURES AND PRACTICES:		
Visual Tank Inspection (external)		15
Visual Tank Inspection (internal)		60
Relief Valve Inspection		15
Piping Inspection		300
Piping Maintenance		120
Valve Inspection		30
Valve Maintenance		350
TOTAL COSTS	116,000	14,000

TABLE 5-10. ESTIMATED TYPICAL CAPITAL AND ANNUAL COSTS ASSOCIATED WITH LEVEL 1 SULFUR TRIOXIDE STORAGE SYSTEM

	Capital Cost (1986 $)	Annual Cost (1986 $/yr)
VESSELS:		
Storage Tanks	114,000	13,000
Immersion Heater	4,800	570
Insulation	18,000	2,100
PIPING AND VALVES:		
Pipework	16,000	1,800
Check Valves (2)	1,100	120
Globe Valves (7)	2,800	330
Relief Valves (2)	3,200	380
Heat Tracing	710	80
Insulation	1,900	220
PROCESS MACHINERY:		
Submerged Centrifugal Pump	6,500	750
INSTRUMENTATION:		
Pressure Gauge	370	45
Liquid Level Gauge	1,500	175
Remote Level Indicator	1,900	220
Local Temperature Indicator	1,900	220
Remote Temperature Indicator	2,200	260
Temperature Control		
- Controller	1,900	220
- Sensor	190	25
- Control Valve	2,800	330
SCRUBBER:		
Brink® Mist Eliminator	27,000	3,100
DIKING:		
3 ft High Concrete Diking	1,400	160
PROCEDURES AND PRACTICES:		
Visual Tank Inspection (external)		15
Visual Tank Inspection (internal)		60
Relief Valve Inspection		30
Piping Inspection		300
Piping Maintenance		120
Valve Inspection		35
Valve Maintenance		400
TOTAL COSTS	210,000	25,000

TABLE 5-11. ESTIMATED TYPICAL CAPITAL AND ANNUAL COSTS ASSOCIATED WITH LEVEL 2 SULFUR TRIOXIDE STORAGE SYSTEM

	Capital Cost (1986 $)	Annual Cost (1986 $/yr)
VESSELS:		
Storage Tank	300,000	35,000
Immersion Heater	4,800	570
PIPING AND VALVES:		
Pipework	30,000	3,500
Reduced Pressure Device	1,500	170
Globe Valves (7)	2,800	200
Relief Valves (2)	3,200	470
Rupture Disks (2)	1,100	130
PROCESS MACHINERY:		
Centrifugal Pump	19,000	2,200
INSTRUMENTATION:		
Pressure Gauges (2)	740	90
Liquid Level Gauge	1,500	175
Remote Level Indicator	1,900	220
Level Alarm	380	45
High-Low Level Shutoff	1,900	220
Local Temperature Indicator	1,900	220
Remote Temperature Indicator	2,200	260
Temperature Alarm	380	45
Temperature Control		
- Controller	1,900	220
- Sensor	190	25
- Control Valve	2,800	330
ENCLOSURE:		
Concrete Building	19,000	2,300
SCRUBBER:		
Acid Scrubber	280,000	33,000
DIKING:		
3 ft. High Concrete Diking	1,400	160

(Continued)

TABLE 5-11. (Continued)

	Capital Cost (1986 $)	Annual Cost (1986 $/yr)
PROCEDURES AND PRACTICES:		
External Tank Inspection		15
Internal Tank Inspection		60
Relief Valve Inspection		300
Piping Inspection		120
Piping Maintenance		120
Valve Inspection		35
Valve Maintenance		400
TOTAL COSTS	679,000	80,000

TABLE 5-12. ESTIMATED TYPICAL CAPITAL AND ANNUAL COSTS ASSOCIATED WITH BASELINE SULFUR TRIOXIDE SULFONATION SYSTEM

	Capital Cost (1986 $)	Annual Cost (1986 $/yr)
VAPORIZER[a] - Cost includes vessels, machinery, piping, controls, and instrumentation for vaporizers (See Table 5-18 for details).	783,000	94,000
SULFONATOR[a] - Cost includes vessels, machinery, piping, controls, and instrumentation for sulfonators (See Table 5-18 for details).	1,150,000	138,000
SCRUBBER: Caustic Venturi Scrubber	240,000	29,000
DIKING: Curbing Around Reactor	1,200	150
TOTAL COSTS	2,174,000	261,000

[a]System cost based on a 20 million pounds per year capacity system obtained from Reference 12.

TABLE 5-13. ESTIMATED TYPICAL CAPITAL AND ANNUAL COSTS ASSOCIATED WITH LEVEL 1 SULFUR TRIOXIDE SULFONATION SYSTEM

	Capital Cost (1986 $)	Annual Cost (1986 $/yr)
VAPORIZER:		
Baseline Cost (see Table 5-12)	783,000	94,000
Add to Baseline:		
- Redundant Temperature Sensors (4)	1,400	175
- Redundant Temperature Alarm	360	175
- Redundant Pressure Indicators (2)	3,600	430
- Redundant Flow Control Loop	5,500	650
- pH Monitoring System	9,000	1,100
SULFONATOR:		
Baseline Cost (see Table 5-12)	1,150,000	138,000
Add to Baseline		
- Redundant Temperature Sensors (12)	4,300	500
- Redundant Temperature Alarm	360	45
- Redundant Pressure Indicators (5)	9,000	1,100
- Redundant Flow Control Loop	5,500	650
- Additional Relief Valves	2,000	230
DIKING:		
3 ft. High Retaining Wall	3,000	360
SCRUBBER:		
Wet Electrostatic Precipitator with Packed Tower	417,000	50,000
ENCLOSURE:		
Steel Building	10,000	1,200
TOTAL COSTS	2,404,000	289,000

TABLE 5-14. EQUIPMENT SPECIFICATIONS ASSOCIATED WITH SULFUR TRIOXIDE STORAGE SYSTEM

Equipment Item	Equipment Specification	Reference
VESSELS:		
Storage Tank	Baseline: 10,000 gal. Carbon Steel Storage Tank, 50 psig Level #1: 10,000 gal. Carbon Steel with 1/8 in. Corrosion Protection, 100 psig Level #2: 10,000 gal. 304 Stainless Steel 100 psig	25, 26, 27, 28
Immersion Heater	75 kw Rating, Electric Bayonet	25
Insulation	2 1/2 in. Thick Covering 10 ft. Diameter by 17 ft. Long Horizontal Storage Tank	26
PIPING AND VALVES:		
Pipework	Baseline: 100 ft. of 2 in. Schedule Carbon Steel Level #1: 100 ft. of 2 in. Schedule 80 Type 304 Stainless Steel Level #2: 100 ft. of 2 in. Schedule 80 Monel®.	29, 30
Check Valve	2 in. Vertical Lift Check Valve, Stainless Steel Construction	25, 26
Globe Valves	2 in. ANSI Class 300, Type 316 Stainless Steel Construction	25, 26
Relief Valve	1 in. x 2 in., ANSI Class 300 inlet and Outlet Flange, Angle Body, Closed Bonnet with Screwed Cap. Type 316 Stainless Steel Body and Trim.	26
Heat Tracing	1/2 in. OD Copper Trace Line, Heat Transfer Cement	26
Insulation	1 1/2 in. Thick CaSi including Aluminum Waterproof Jacket	26

(Continued)

TABLE 5-14. (Continued)

Equipment Item	Equipment Specification	Reference
Reduced Pressure Device	Double Check Valve Type Device With Internal Air Gap and Relief Valve	25
Rupture Disk	1 in. Monel® Disk and Carbon Steel Holder	27, 31, 32
PROCESS MACHINERY:		
Centrifugal Pump	Baseline: Single Stage, Alloy 20 Construction, Stuffing Box Level #1: Single Stage Submerged, Alloy 20 Construction, Double Mech. Seal Level #2: Magnetically-coupled, Construction, Double Mech. Seal	25, 26, 33
INSTRUMENTATION:		
Pressure Gauge	Diaphragm Sealed, Hastelloy C Diaphragm, 0-200 psi	25, 26, 34
Liquid Level Gauge	Differential Pressure Type	25, 34
Level Indicator	Differential Pressure Type Indicator	25, 34
Level Alarm	Indicating and Audible Alarm	25, 35, 36
High-low Level Shutoff	Solenoid Valve, Switch, and Relay System	25, 26, 34
Temperature Indicator/Controller	Thermocouple, Thermowell, Electronic Indicator/Controller	25, 35, 34
Temperature Alarm	Indicating and Audible Alarm	25, 35, 36
ENCLOSURES:		
Building	Level #2: 10 in. Concrete Walls, 26-Gauge Steel Roof	35

(Continued)

TABLE 5-14. (Continued)

Equipment Item	Equipment Specification	Reference
SCRUBBERS:	Level #1: Brink® Mist Eliminator, Carbon Steel Construction, Water Spray, 500 ACFM Capacity Level #2: Acid Scrubber with Demister, Packed Tower with Ceramic Saddles, Circulating Pump with 96-98% H_2SO_4. Spray Tower with Brink® Mist Eliminator, Stainless Steel Construction, Water Spray, 1000 ACFM Capcity	37
DIKING:	Level #1 and #2: 6 in. Concrete Walls, 3 ft. High	35

TABLE 5-15. DETAILS OF MATERIAL AND LABOR COSTS ASSOCIATED WITH BASELINE SULFUR TRIOXIDE STORAGE SYSTEM

	Materials Cost	Labor Cost	Direct Costs	Indirect Costs	Capital Cost
			(1986 $)		
VESSELS:					
Storage Tank	29,150	13,100	42,250	14,800	63,000
Immersion Heater	2,650	660	3,310	830	4,800
Insulation	4,800	7,300	12,100	4,230	18,000
PIPING AND VALVES:					
Pipework	1,400	5,230	6,640	2,320	9,900
Check Valve	300	50	350	130	530
Globe Valves (7)	1,750	180	1,930	680	2,800
Relief Valve	1,000	50	1,100	380	1,600
Heat Tracing	190	290	480	170	710
Insulation	500	750	1,250	440	1,900
PROCESS MACHINERY:					
Centrifugal Pump	1,900	800	2,700	940	4,000
INSTRUMENTATION:					
Liquid Level Gauge	800	200	1,000	350	1,500
Local Temperature Indicator	1,000	250	1,250	440	1,900
Temperature Control					
- Controller	1,000	250	1,250	440	1,900
- Sensor	100	25	125	45	190
- Control Valve	1,500	380	1,880	660	2,800
TOTAL COSTS	48,000	30,000	78,000	27,000	116,000

TABLE 5-16. DETAILS OF MATERIAL AND LABOR COSTS ASSOCIATED WITH LEVEL 1 SULFUR TRIOXIDE STORAGE SYSTEM

	Materials Cost	Labor Cost	Direct Costs	Indirect Costs	Capital Cost
			(1986 $)		
VESSELS:					
Storage Tank	53,000	24,000	77,000	27,000	114,000
Immersion Heater	2,650	660	3,310	830	4,800
Insulation	4,800	7,300	12,100	4,230	18,000
PIPING AND VALVES:					
Pipework	2,700	7,900	10,600	3,700	16,000
Check Valves (2)	600	100	700	130	1,100
Globe Valves (7)	1,750	180	1,930	680	2,800
Relief Valves (2)	2,000	200	2,200	700	3,200
Heat Tracing	190	290	480	170	710
Insulation	500	750	1,250	440	1,900
PROCESS MACHINERY:					
Submerged Centrifugal Pump	3,000	1,300	4,300	1,500	6,500
INSTRUMENTATION:					
Pressure Gauge	200	50	250	90	370
Liquid Level Gauge	800	200	1,000	350	1,500
Remote Level Indicator	1,000	250	1,250	440	1,900
Local Temperature Indicator	1,000	250	1,250	440	1,900
Remote Temperature Indicator	1,200	300	1,500	530	2,200
Temperature Control					
- Controller	1,000	250	1,250	440	1,900
- Sensor	100	25	125	45	190
- Control Valve	1,500	380	1,880	660	2,800
SCRUBBER:					
Water Scrubber	12,000	6,000	18,000	6,300	27,000
DIKING:					
3 ft High Concrete Diking	390	520	910	320	1,400
TOTAL COSTS	90,000	51,000	141,000	49,000	210,000

TABLE 5-17. DETAILS OF MATERIAL AND LABOR COSTS ASSOCIATED WITH LEVEL 2 SULFUR TRIOXIDE STORAGE SYSTEM

	Materials Cost	Labor Cost	Direct Costs	Indirect Costs	Capital Cost
			(1986 $)		
VESSELS:					
Storage Tank	139,000	63,000	202,000	71,000	300,000
Immersion Heater	2,650	660	3,310	830	4,800
PIPING AND VALVES:					
Pipework	11,000	9,000	20,000	7,000	30,000
Reduced Pressure Device	800	200	1,000	350	1,500
Globe Valves (7)	1,750	180	1,930	680	2,800
Relief Valves (2)	2,000	200	2,200	700	3,200
Rupture Disks (2)	650	80	730	260	1,100
PROCESS MACHINERY:					
Centrifugal Pump	9,000	3,900	12,900	4,500	19,000
INSTRUMENTATION:					
Pressure Gauges (2)	400	100	500	180	740
Liquid Level Gauge	800	200	1,000	350	1,500
Remote Level Indicator	1,000	250	1,250	440	1,900
Level Alarm	200	50	250	90	380
High-Low Level Shutoff	1,000	250	1,250	440	1,900
Local Temperature Indicator	1,000	250	1,250	440	1,900
Remote Temperature Indicator	1,200	300	1,500	530	2,200
Temperature Alarm	200	50	250	90	380
Temperature Control					
- Controller	1,000	250	1,250	440	1,900
- Sensor	100	25	125	45	190
- Control Valve	1,500	380	1,880	660	2,800
ENCLOSURE:					
Concrete Building	6,100	6,600	13,000	4,500	19,000
SCRUBBER:					
Acid Scrubber	130,000	59,000	189,000	66,000	280,000
DIKING:					
3 ft High Concrete Dike	390	520	910	320	1,400
TOTAL COSTS	312,000	145,000	457,000	160,000	679,000

TABLE 5-18. EQUIPMENT SPECIFICATIONS ASSOCIATED WITH SULFUR TRIOXIDE SULFONATION

Equipment Item	Equipment Specification	Reference
VAPORIZER:	System includes: 316 S.S. vaporizer, 316.S.S. piping, positive displacement metering pump, interlocks, air compressor, air chiller, drier, heat exchanger, local and remote temperature sensor/controller, local flow indicator/controller, and local pressure indicator.	12,25
SULFONATOR:	System includes: 316 S.S. falling film reactor with 20 million lb/yr capacity, cyclone separator, heat exchanger, interlocks recycle pump, local and remote temperature controller, local flow controller, relief valve, and digester.	12,25
PIPING AND VALVES:		
Relief Valve	2 in. x 3 in. Class 300 Inlet and Outlet Flange, Angle Body, Closed Bonnet With Screwed Cap, 316 S.S. Body, Monel® Trim	26
Rupture Disk	2 in. Monel® Disk and Carbon Steel Holder	27,31,32
INSTRUMENTATION:		
Temperature Sensor	Thermocouple and Associated Thermowell	25,26,36
Temperature Alarm	Indicating and Audible Alarm	26,35,36
Temperature Switch	Two-Stage Switch with Independently Set Actuation	25,36
Remote Temperature Indicator	Transmitter and Associated Electronics Indicator	25,36
Remote Pressure Indicator	Transducer, Transmitter and Electronic Indicator	25,36

(Continued)

TABLE 5-18. (Continued)

Equipment Item	Equipment Specification	Reference
Flow Control Loop	2 in. Globe Control Valve, Monel® Trim, Flowmeter and PTD Controller	25,36
Flow Interlock System	Solenoid Valve, Switch, and Relay System	25,36
pH Monitoring System	Electrode, Electrode Chamber, Amplifier-Transducer and Indicator	25,36
DIKING:	Baseline: 6 in. High Concrete Curbing Level #1: 3 ft. High Concrete Retaining	35
SCRUBBER:	Baseline: Venturi Scrubber with caustic spray	12,25
	Level #1: Electrostatic Precipitator and Packed Tower System	19,25

TABLE 5-19. DETAILS OF MATERIAL AND LABOR COSTS ASSOCIATED WITH BASELINE SULFUR TRIOXIDE SULFONATION SYSTEM

	Materials Cost	Labor Cost	Direct Cost	Indirect Cost	Capital Cost
			(1986 $)		
VAPORIZER:[a]	375,000	170,000	545,000	136,000	783,000
- Includes vessels, machinery, piping, controls, and instrumentation for vaporizer (see Table 5-18 for details).					
SULFONATOR:[a]	550,000	250,000	800,000	200,000	1,150,000
- Includes vessels, machinery, piping, controls, and instrumentation for sulfonator (see Table 5-18 for details).					
SCRUBBER:					
Caustic Venturi Scrubber	115,000	52,000	167,000	42,000	240,000
DIKING:					
Curbing Around Reactor	500	350	850	210	1,200
TOTAL COSTS	1,041,000	472,000	1,513,000	378,000	2,174,000

[a]System costs based on a 20 million pounds per year capacity system obtained from Reference 12.

TABLE 5-20. DETAILS OF MATERIAL AND LABOR COSTS ASSOCIATED WITH LEVEL 1 SULFUR TRIOXIDE SULFONATION SYSTEM

	Materials Cost	Labor Cost	Direct Cost	Indirect Cost	Capital Cost
			(1986 $)		
VAPORIZER:					
Baseline Cost (See Table 5-19)	375,000	170,000	545,000	136,000	783,000
Add to Baseline:					
- Redundant Temperature Sensors (4)	800	200	1,000	240	1,400
- Redundant Temperature Alarm	200	50	250	60	360
- Redundant Pressure Indicators (2)	2,000	500	2,500	620	3,600
- Redundant Flow Control Loop	3,000	750	3,750	950	5,500
- pH Monitoring System	5,000	1,300	6,300	1,600	9,000
SULFONATOR:					
Baseline Cost (See Table 5-19)	550,000	250,000	800,000	200,000	1,150,000
Add to Baseline					
- Redundant Temperature Sensors (12)	2,400	600	3,000	720	4,300
- Redundant Temperature Alarm	200	50	250	60	360
- Redundant Pressure Indicators (5)	5,000	1,250	6,250	1,550	9,000
- Redundant Flow Control Loop	3,000	750	3,750	950	5,500
- Second Relief Valve	1,300	50	1,350	340	2,000
DIKING:					
3 ft. High Retaining Wall	900	1,200	2,100	530	3,000
SCRUBBER: Electrostatic Precipitator with Packed Tower	200,000	90,000	290,000	73,000	417,000
ENCLOSURE: Steel Building	4,600	2,300	6,900	2,400	10,000
TOTAL COSTS	1,154,000	519,000	1,673,000	419,000	2,404,000

5.8.5 Methodology

Tables are provided for control schemes associated with storage and process facilities for liquid sulfur trioxide showing capital, operating, and total annual costs. The tables are broken down into subsections comprising vessels, piping and valves, process machinery, instrumentation, and procedures and practice. The presentation of the costs in this manner allows for easy comparison of costs for specific items, different levels, and different systems.

Capital Cost--All capital costs presented in this report are shown as total fixed capital costs. Table 5-21 defines the cost elements comprising total fixed capital as it is used here.

The computation of total fixed capital as shown in Table 5-21 begins with the total direct cost for the system under consideration. This total direct cost is the total direct installed cost of all capital equipment comprising the system. Depending on the specific equipment item involved, the direct capital cost was available or was derived from uninstalled equipment costs by computing costs of installation separately. To obtain the total fixed capital cost, other costs obtained by utilizing factors are added to the total direct costs.

The first group of other cost elements is indirect costs. These include engineering and supervision, construction expenses, and various other expenses such as administration expenses, for example. These costs are computed by multiplying total direct costs by a factor shown in Table 5-21. The factor is approximate, is obtained from the cost literature, and is based on previous experience with capital projects of a similar nature. Factors can have a range of values and vary according to technology area and for individual technologies within an area. Appropriate factors were selected for use in this report based on judgement and experience.

TABLE 5-21. FORMAT FOR TOTAL FIXED CAPITAL COST

Item No.	Item	Cost
1	Total Material Cost	-
2	Total Labor Cost	-
3	Total Direct Cost	Items 1 + 2
4	Indirect Cost Items (Engineering & Construction Expenses)	0.35 x Item 3[a]
5	Total Bare Module Cost	Items (3 + 4)
6	Contingency	(0.05 x Item 5)[b]
7	Contractor's Fee	0.05 x Item 5
8	Total Fixed Capital Cost	Items (5 + 6 + 7)

[a] For storage facilities, the indirect cost factor is 0.35. For process facilities, the indirect cost factor is 0.25.

[b] For storage facilities, the contingency cost factor is 0.05. For process facilities, the contingency cost factor is 0.10.

When the indirect costs are added to the total direct costs, total bare module cost is obtained. Some additional cost elements such as contractor's fee and contingency are calculated by applying and adding appropriate factors to the total bare module cost as shown in Table 5-21 to obtain the total fixed capital cost.

Annual Cost--Annual costs are obtained for each of the equipment items by applying a factor for both capital recovery and for maintenance expenses to the direct cost of each equipment item. Table 5-22 defines the cost elements and appropriate factors comprising these costs. Additional annual costs are incurred for procedural items such as valve and vessel inspections, for example. When all of these individual costs are added, the total annual cost is obtained.

Sources of Information--

The costs presented in this report are derived from cost information in existing published sources and also from recent vendor information. It was the objective of this effort to present cost levels for liquid sulfur trioxide process and storage facilities using the best costs for available sources. The primary sources of cost information are Peters and Timmerhaus (25), Chemical Engineering (38), and Valle-Riestra (39) supplemented by other sources and references where necessary. Adjustments were made to update all costs to a June 1986 dollar basis. In addition, for some equipment items, well-documented costs were not available and they had to be developed from component costs.

Costs in this document reflect the "typical" or "average" representation for specific equipment items. This restricts the use of data in this report to:

- Preliminary estimates used for policy planning;
- Comparison of relative costs of different levels or system; and

TABLE 5-22. FORMAT FOR TOTAL ANNUAL COST

Item No.	Item	Cost
1	Total Direct Cost	-
2	Capital Recovery on Equipment Items	0.163[a] x Item 1
3	Maintenance Expense on Equipment Items	0.01 x Item 1
4	Total Procedural Items	-
5	Total Annual Cost	Items (2 + 3 + 4)

[a]Based on a capital recovery factor at 10 percent cost of capital for 10 years.

- Approximations of costs that might be incurred for a specific application.

The costs in this report are considered to be "order of magnitude" with a ±50 percent margin. This is because the costs are based on preliminary estimates and many are updated from literature sources. Large departures from the design basis of a particular system presented in this manual or the advent of a different technology might cause the system cost to vary by a greater extent than this. If used as intended, however, this document will provide a reasonable source of preliminary cost information for the facilities covered.

When comparing costs in this manual to costs from other references, the user should be sure the design bases are comparable and that the capital and annual costs as defined here are the same as the costs being compared.

Cost Updating--

All costs in this report are expressed in June 1986 dollars. Costs reported in the literature were updated using cost indices for materials and labor.

Costs expressed in base year dollars may be adjusted to dollars for another year by applying cost indices as shown in the following equation:

$$\text{new base year cost} = \text{old base year cost} \times \frac{\text{new base year index}}{\text{old base year index}}$$

The Chemical Engineering (CE) Plant Cost Index was used in updating cost for this report. For June 1986, the index is 316.3.

Equipment Cost--

Most of the equipment costs presented in this manual were obtained directly from literature sources of vendor information and correspond to a specific design standard. Special cost estimating techniques, however, were

used in determining the costs associated with vessels, piping systems, scrubbers, diking, and enclosures. The techniques used are presented in the following subsections of this manual.

Vessels--The total purchased cost for a vessel, as dollars per pound of weight of fabricated unit free on board (f.o.b.) with carbon steel as the basis (January 1979 dollars) were determined using the following equation for Peters and Timmerhaus (25):

$$\text{Cost} = 50\ [\text{Weight of Vessel in Pounds}]^{-0.34}$$

The vessel weight is determined using appropriate design equations as given by Peters and Timmerhaus (25) which allow for wall thickness adjustments for corrosion allowances, for example. The vessel weight is increased by a factor of 0.15 for horizontal vessels and 0.20 for vertical vessels to account for the added weight due to nozzles, manholes, and skirts or saddles. Appropriate factors are applied for different materials of construction as given in Peters and Timmerhaus (25). The vessel costs are updated using cost factors. Finally a shipping cost amounting to 10 percent of the purchased cost is added to obtain the delivered equipment cost.

Piping--Piping costs were obtained using cost information and data presented by Yamartino (29) and Barnett (30). A simplified approach is used in which it is assumed that a certain length of piping containing a given number of valves, flanges, and fittings is contained in the storage or process facility. The data presented by Yamartino (29) and Barnet (30) permit cost determinations for various lengths, sizes, and types of piping systems. Using these factors, a representative estimate can be obtained for each of the storage and process facilities.

Diking--Diking costs were estimated using Mean's Manual (35) for reinforced concrete walls. Several assumptions were made in determining the costs. The dike must contain the entire contents of a tank in the event of a

leak or release. Two dike sizes are considered: a three-foot high dike, (six-inches thick) and a top-of-tank height dike (ten inches thick). The tanks are raised off the ground and are not volumetrically included in the volume enclosed by the diking. These assumptions facilitate cost determination for any size diking system.

Enclosures--Enclosure costs were estimated using Mean's Manual (35) for both reinforced concrete and steel-walled buildings. The buildings are assumed to enclose the same area and volume as the top-of-tank height dikes. The concrete building is ten-inches thick with a 26-gauge steel roof and a metal door. The steel building has 26-gauge roofing, siding, and metal door. The cost of a ventilation system was determined using a typical 1,000 scfm unit and doubling the cost to account for ductwork and requirements for the safe enclosure of hazardous chemicals.

Scrubbers--Scrubber costs were estimated using the following equation from the Gard (37) manual for scrubbers. The costs were based on the actual cubic feet per minute of flow at a chamber velocity of 600 feet/minute.

$$\text{Costs} = 0.235 \times (\text{ACFM} + 43{,}000)$$

A release rate of 10,000 ft^3/minute was assumed for the storage vessel systems and an appropriate rate was determined for the process system based on the quantity of hazardous chemicals present in the system at any one time. For the sulfonation reactor system, a rate of 1,000 ft^3/minute was assumed. In addition to the tower, the costs also include pumps and a storage tank for the scrubbing medium. The costs presented are updated to June 1986 dollars.

Installation Factors--

Installation costs were developed for all equipment items included in both the process and storage systems. The costs include both the material and labor costs for installation of a particular piece of equipment. The costs were obtained directly from literature sources and vendor information or

indirectly by assuming a certain percentage of the purchased equipment cost through the use of estimating factors obtained from Peters and Timmerhaus (25) and Valle-Riestra (39). Table 5-23 lists the cost factors used or the reference from which the cost was obtained directly. Many of the costs obtained from the literature were updated to June 1986 dollars using a 10 percent per year rate of increase for labor and cost indices for materials associated with installation.

TABLE 5-23. FORMAT FOR INSTALLATION COSTS

Equipment Item	Factor or Reference
Vessels:	
Storage Tank	0.45
Expansion Tank	0.25
Piping and Valves:	
Pipework	Ref. 29 and 30
Expansion Loop	Ref. 26
Reduced Pressure Device	Ref. 26
Check Valves	Ref. 26
Gate Valves	Ref. 26
Ball Valves	Ref. 26
Excess Flow Valves	Ref. 26
Angle Valves	Ref. 35
Relief Valves	Ref. 26
Rupture Disks	Ref. 26
Process Machinery:	
Centrifugal Pump	0.43
Instrumentation:	
All Instrumentation Items	0.25
Enclosures:	Ref. 35
Diking:	Ref. 35
Scrubbers:	0.45

SECTION 6

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APPENDIX A
GLOSSARY

This glossary defines selected terms used in the text of this manual which might be unfamiliar to some users or which might be used differently by different authors.

Accidental release: The unintentional spilling, leaking, pumping, purging, emitting, emptying, discharging, escaping, dumping, or disposing of a toxic material into the environment in a manner that is not in compliance with a plant's federal, state, or local environmental permits and/or that creates toxic concentrations in the air that are a potential health threat to the surrounding community.

Cavitation: The formation and collapse of vapor bubbles in a flowing liquid. Specifically, the formation and collapse of vapor cavities in a pump when there is sufficient resistance to flow at the inlet side.

Chlorofluorocarbons: Organic compounds containing chlorine and/or fluorine atoms within the molecule.

Creep failure: Failure of a piece of metal as a result of creep. Creep is time-dependent deformation as a result of stress. Metals will deform when exposed to stress. High levels of stress can result in rapid deformation and rapid failure. Lower levels of stress can result in slow deformation and protracted failure.

Deadheading: Closing or nearly closing or blocking the discharge outlet or piping of an operating pump or compressor.

Electromotive Series of Metals: A list of metals and alloys arranged according to their standard electrode potential, which also reflects their relative corrosion potential.

Enthalpy: A thermodynamic property of a chemical related to its energy content at a given condition of temperature, pressure, and physical state. Enthalpy is the internal energy added to the product of pressure times volume. Numerical values of enthalpy for various chemicals are always based on the change in enthalpy from an arbitrary reference pressure, temperature, and physical state, since the absolute value cannot be measured.

Facility: A location at which a process or set of processes is used to produce, refine or repackage chemicals, or a location where a large enough inventory of chemicals is stored so that a significant accidental release of a toxic chemical is possible.

Hazard: A source of danger. The potential for death, injury or other forms of damage to life and property.

Hygroscopic: Readily absorbing and retaining moisture, usually in reference to readily absorbing moisture from the air.

Killed steel: Steel that is deoxidized with a strong deoxidizing agent such as silicon or aluminum to reduce the oxygen content to such a level that no reaction occurs between carbon and oxygen during solidification. Such a steel will have a smaller grain size than a steel that is not killed. The grain size affects the physical and chemical properties of the steel. Fully-killed steel is fully deoxidized and has a smaller grain size than semi-killed steel which is partially deoxidized and has a smaller grain size than steel that is not killed.

Mild steel: Carbon steel containing a maximum of about 0.25% carbon. Mild steel can be used where severe corrodants are not encountered or where protective coatings can be used to prevent or reduce corrosion rates to acceptable levels.

Mitigation: Any measure taken to reduce the severity of the adverse effects associated with the accidental release of a hazardous chemical.

Olefinic hydrocarbons: A specific subgroup of aliphatic hydrocarbons sharing the common characteristic of at least one unsaturated carbon-to-carbon atomic bond in the hydrocarbon molecule. Aliphatic hydrocarbons are hydrocarbons with a basic straight or branched chain structure, in contrast with ring structured compounds.

Passivation film: A layer of oxide or other chemical compound of a metal on its surface that acts as a protective barrier against corrosion or further chemical reaction.

Plant: A location at which a process or set of processes is used to produce, refine, or repackage chemicals.

Prevention: Design and operating measures applied to a process to ensure that the primary containment of toxic chemicals is maintained. Primary containment means confinement of toxic chemicals within the equipment intended for normal operating conditions.

Process: The sequence of physical and chemical states and operations during the production, refining, or repackaging of chemicals.

Process machinery: Process equipment such as pumps, compressors, or agitators that would not be categorized as piping or vessels.

Protection: Measures taken to capture or destroy a toxic chemical that has breached primary containment but not yet entered the external environment.

Toxicity: A measure of the adverse health effects of exposure to a chemical.

APPENDIX B

TABLE B-1. METRIC (SI) CONVERSION FACTORS

Quantity	To Convert From	To	Multiply By
Length:	in	cm	2.54
	ft	m	0.3048
Area:	in^2	cm^2	6.4516
	ft^3	m^3	0.0929
Volume:	in^3	cm^3	16.39
	ft^3	m^3	0.0283
	gal	m^3	0.0038
Mass (weight):	lb	kg	0.4536
	short ton (ton)	Mg	0.9072
	short ton (ton)	metric ton (t)	0.9072
Pressure:	atm	kPa	101.3
	mm Hg	kPa	0.133
	psia	kPa	6.895
	psig	kPa*	(psig+14.696)x(6.895)
Temperature:	°F	°C*	(5/9)x(°F-32)
	°C	K*	°C+273.15
Caloric Value;	Btu/lb	kJ/kg	2.326
Enthalpy:	Btu/lbmol	kJ/kgmol	2.326
	kcal/gmol	kJ/kgmol	4.184
Specific-Heat Capacity:	Btu/lb-°F	kJ/kg-°C	4.1868
Density:	lb/ft^3	kg/m^3	16.02
	lb/gal	kg/m^3	119.8
Concentration:	oz/gal	kg/m^3	
	quarts/gal	cm^3/m^3	25,000
Flowrate:	gal/min	m^3/min	0.0038
	gal/day	m^3/day	0.0038
	ft^3/min	m^3/min	0.0283
Velocity:	ft/min	m/min	0.3048
	ft/sec	m/sec	0.3048
Viscosity:	centipoise (CP)	kg/m-s	0.001

*Calculate as indicated.